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ORIGINAL ARTICLE

Asymmetry in foot pressure distribution patterns during bend sprinting

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ABSTRACT

In curved track sprinting under high running speeds, such as in the short distance events of athletics, there are left-right differences in the exertion of force. However, the characteristics of the differences in foot pressure distribution related to force production during a curved track sprint have not yet been investigated. The purpose of this study was to clarify the asymmetry of foot pressure distribution during bend sprinting. Thirteen male university sprinters performed three maximum-effort 60 m sprints on a curved track with a radius of 37.9 m. Foot pressure was measured using a wireless insole pressure sensor system with 13 sensors per foot. The maximum foot pressure and the pressure of each sensor at the time of maximum foot pressure were calculated. No significant difference was observed between the left and right legs in terms of the maximum foot pressure. However, the pressure ratio at the sensor located near the fifth toe (Ch0) was significantly higher in the right leg than that in the left leg. By contrast, the pressure ratios at the sensors located around the first cuneiform (Ch8 and Ch10) were significantly higher in the left leg than in the right leg. These results suggest that during bend sprinting, mechanical loading is greater around the first toe in the right foot than in the left foot and around the medial midfoot in the left foot than in the right foot. These findings have implications for the performance enhancement and injury prevention of sprinters.
Keywords: Biomechanics, Sprint motion, Curvilinear, Foot pressure, Asymmetry.

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INTRODUCTION

In short-distance track events, the maximum sprinting speed observed in the middle phase of a race has been reported to have a significant impact on performance (Hanon & Gajer, 2009; Mackala, 2007). However, unlike the 100 m sprint, the 200 m and 400 m races require athletes to run on a curved track because of the design of standard athletics tracks. Furthermore, it has been reported that maximum sprinting speed often occurs in the curved section of a track (Ferro & Floria, 2013; Quinn, 2009). Thus, achieving high sprinting speeds on a curved track is one of the key challenges for improving performance in the 200 m and 400 m events.

To run on a curved track, in addition to generating force in the anteroposterior and vertical directions, as in straight-track running, athletes must also exert force in the lateral direction, namely, centripetal force. Theoretically, this force is expressed as "*body weight* × *velocity*² / *radius of curvature*," meaning that the required force varies depending on the running speed and lane position. A characteristic strategy for generating this force is to lean the body inward toward the centre of the curve. Previous research on sprinting mechanics on curved tracks has generally shown that sprinting speed is lower on curved tracks than on straight tracks (Chang and Kram, 2007; Churchill et al.,2015; Churchill et al.,2016; Stoner & Ben-sira, 1979). Additionally, studies have reported asymmetries in lower limb kinematics and kinetics during curved-track sprinting, as well as differences from straight-track running that vary between the left and right sides (Churchill et al.,2015; Churchill et al.,2016; Alt et al., 2015; Ishimura & Sakurai, 2016; Judson et al.,2019). However, research on the characteristics of running mechanics on curved tracks remains limited and no consistent findings have been established.

The kinematic and kinetic characteristics of running on a curved track have primarily been investigated using motion-analysis methods. However, while ground reaction forces, which play a crucial role in determining body movement, have been examined, no study has specifically analysed the distribution of these forces. During running, it has been reported that when the peak ground reaction force occurs, foot pressure distribution increases around the first metatarsophalangeal joint (Cavanagh, 1987). However, during curved-track running, because athletes lean their bodies inward toward the centre of the curve, it is presumed that the proportion of foot pressure distributed in the inward and outward directions of the track increases. However, the extent of the shift remains unclear. Furthermore, to examine the sprinting mechanics on curved tracks, it is necessary to conduct investigations under high-speed conditions, as suggested by the theoretical considerations mentioned earlier.

The purpose of this study was to clarify the asymmetry of foot pressure distribution during bend sprinting.

MATERIAL AND METHODS

Participants

Thirteen male university sprinters participated in this experiment (age: 19 ± 1 years, height: 1.75 ± 0.05 m, body mass: 69.1 ± 5.1 kg, World Athletics Score in their specialized event: 886 ± 93). The average IAAF score of the participants in this study corresponded to an estimated 100 m sprint time of 11.00 seconds. Prior to the experiment, the purpose, procedures, and potential risks were explained both in writing and verbally, and written informed consent was obtained from all the participants. This study was approved by the Ethics Committee of the Japan Institute of Sports Sciences.

Measures

The experimental trials consisted of three maximum-effort 60 m sprints on a curved track. The experiment was conducted at an indoor facility with an all-weather synthetic track surface. For the curved-track trials, a curve with a radius of 37.9 m - equivalent to lane 1 of a standard athletics track, was used. This setup was based on the findings of previous study (Greene, 1985), which indicated that smaller curve radii resulted in greater performance decline. The participants were allowed to rest adequately between trials at their discretion. Prior to the experiment, reflective markers were attached to the participants based on a Plug-in Gait model (Davis et al.,1991).

The foot pressure was measured using a wireless insole pressure sensor system (OpenGo; Moticon GmbH, Germany). As described in previous studies (Braun et al.,2015; Oerbekke et al.,2017; Stöggl et al.,2017; Nagahara & Morin,2018), the device used in this experiment contained 13 embedded sensors per foot, for a total of 26 sensors, and was fully wireless. Sensor placement is shown in Figure 1. The sampling frequency was set to 50 Hz. Prior to the measurement, the system was calibrated using measurement and analysis software (Moticon, Moticon Inc., Germany). The participants were seated with both legs suspended in air during calibration, and data collection was conducted during the trials. All participants wore the same type of shoe (AIR ZOOM PEGASUS; NIKE, USA). The preinstalled insoles were removed, and the insole pressure sensors were inserted. The shoelaces were tightened to ensure a secure fit and minimize foot movement inside the shoes during the trials.

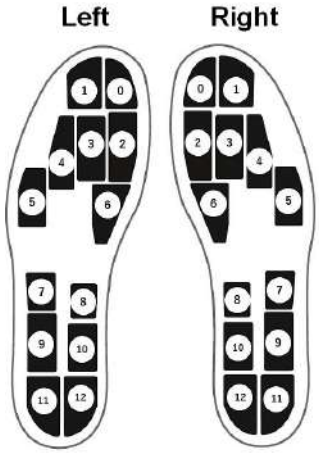

Figure 1. Location of each sensor buried in the measuring instrument. Adapted illustrations from Moticon Inc. manuals.

The measurement section was set approximately 45 m from the start, and data were collected. The printing motion was recorded using an optical 3D motion analysis system (Vicon-MX; Oxford Metrics Ltd., Oxford, UK) with a sampling frequency of 250 Hz. In the 3D measurement coordinate system, the Y-axis was defined as the anteroposterior direction, X-axis as the mediolateral direction, and Z-axis as the vertical direction. Additionally, a high-speed camera (LUMIX FZ300, Panasonic, Japan) was used to record the entire trial from start to end. Owing to software limitations, synchronizing the foot pressure sensor data with the motion data is challenging. Therefore, synchronization was performed using video footage recorded by the camera.

Procedures

Using the motion analysis software Vicon Nexus, the three-dimensional coordinates of the attached body markers were computed by appropriately processing the data in accordance with the Plug-in Gait protocol.

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The whole-body centre of mass was calculated and was time-differentiated. The average resultant velocity in the X- and Y-axes over one running cycle was defined as the running speed. The trial with the highest running speed was selected for the foot pressure distribution analysis. For the foot pressure distribution analysis, the entire foot pressure dataset recorded using the aforementioned measurement and analysis software was transferred to a personal computer. Recorded video footage was used to count the number of steps, and the steps within the motion measurement section were identified. Based on the foot pressure data from the identified steps, the maximum foot pressure and the pressure ratio of each sensor at the time of maximum foot pressure were calculated.

Statistical analysis

A paired t-test was used to examine the differences between the left and right legs during curved-track sprinting. The significance level was set at less than 5%. The effect sizes were calculated using Cohen's d. Statistical analyses were performed using the IBM SPSS Statistics software (v. 22.0, SPSS Inc., Chicago, Illinois, USA).

RESULTS

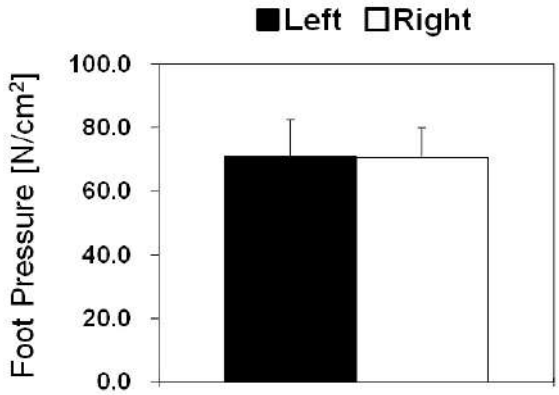
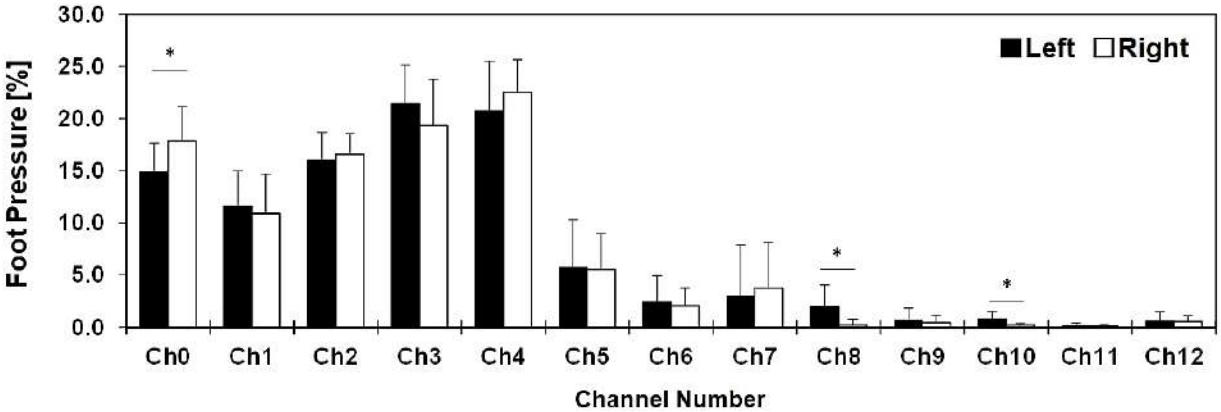


Figure 2. Maximum foot pressure during the left- and right-leg support phases. Black bars represent the left leg and white bars represent the right leg.



*Note. *: significant difference between left and right legs ($p < .05$).*

Figure 3. Differences in foot pressure ratio of each sensor between the left and right legs at the time of maximum foot pressure. Black bars represent the left leg and white bars represent the right leg.

Figure 2 shows the maximum foot pressure values for the left and right legs during the curved-track sprinting. No significant difference was observed between the legs in terms of maximum foot pressure (p = .30; d = 0.02). Figure 3 shows the pressure ratio of each sensor at the time of the maximum foot pressure.

The pressure ratio at Ch0 was significantly higher in the right leg than in the left leg (p = .03, d = 0.98). In contrast, the pressure ratios at Ch8 and Ch10 were significantly higher in the left leg than in the right leg (p = .01, d = 1.22; p = .02, d = 1.17, respectively).

DISCUSSION

This study aimed to clarify the asymmetry of foot pressure distribution during bend sprinting. The results revealed that while there was no difference in the maximum foot pressure between the left and right legs, the distribution ratio differed between them. The running speed in this study was 8.75 ± 0.15 m/s. This value is comparable to that reported in previous studies (Ishimura & Sakurai, 2016) on sprinting mechanics on curved tracks, indicating that the experimental setup for curved-track sprinting was appropriate.

At high running speeds, forefoot contact occurs during the stance phase, which reduces the ground contact time. In this study, 92.8 ± 7.7% of the contacts occurred within Ch0–6. Therefore, to improve performance, specifically to generate greater force, it is necessary to exert force in areas with a high load distribution. The results of this study showed that the pressure ratio at Ch0 was significantly higher in the right leg than that in the left leg. During curved-track sprinting, athletes lean their bodies inward toward the centre of the curve. This likely increases the loading toward the fifth toe on the left foot and toward the first toe on the right foot. The findings for Ch0 support this assumption. However, no significant difference between the legs was observed in the pressure ratio at Ch5. Judson et al. (2019) reported that throughout the entire stance phase during curved-track sprinting, the centre of pressure in the left foot was positioned laterally relative to the second metatarsal head, whereas in the right foot, it did not differ from straight-track running. In this study, only the pressure ratio at the time of maximum foot pressure—corresponding to the mid-stance phase—was analysed, and time-series analysis was not conducted. This may explain the discrepancy between findings. In other words, time-series changes in foot pressure distribution during curved-track sprinting may differ between the left and right legs.

The pressure ratios at Ch8 and Ch10 were significantly higher in the left leg than in the right leg. This result suggests that, in the left foot, greater mechanical loading occurs around the first cuneiform, a part of the midfoot, at the time of maximum foot pressure than in the right foot. The medial longitudinal arch plays a crucial role in shock absorption and energy transfer during weight bearing activities. Differences in arch height have been associated with variations in running-related injuries (Williams et al., 2001). Regarding lower-limb joint kinetics during curved-track sprinting, Judson et al. (2019) reported that the midfoot joint moment in the left foot was greater than that in the right foot. The findings of this study support previous research, suggesting that the left foot experiences greater loading on the medial longitudinal arch than the right foot, potentially increasing the risk of running injuries due to medial longitudinal arch dysfunction. No significant difference was observed in maximum foot pressure between the left and right legs during the stance phase. Previous studies on ground reaction forces during maximum-effort sprinting have also reported no significant difference in vertical ground reaction forces between legs (Churchill et al.,2016), supporting the results of this study.

To replicate high-speed conditions, wireless insole sensors were utilized in this study. However, it has been reported that the ground reaction forces estimated from the wireless insole pressure sensors used in this

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study tend to be lower than actual values (Stöggl et al.,2017). Additionally, measuring spatiotemporal variables and the vertical component of ground reaction forces during sprinting, which involves a short ground contact time, has been reported to be challenging (Nagahara & Morin,2018). Therefore, rather than using the absolute values of the measured pressure, this study examined the differences in the distribution between the left and right legs using pressure ratios. Future research should address limitations such as time resolution and number of sensors to further investigate time-series changes in foot pressure during curved-track sprinting.

CONCLUSION

The purpose of this study was to clarify the asymmetry of foot pressure distribution during bend sprinting. The results revealed that during curved-track sprinting, mechanical loading was greater around the first toe in the right foot than in the left foot, and around the first cuneiform, a part of the midfoot, in the left foot than in the right foot. For performance enhancement, using spike shoes with pins positioned in areas of high load distribution may have a positive effect. Additionally, for injury prevention, preventive measures such as using insoles to support the first cuneiform area of the left foot, which experiences high mechanical loading, may help reduce the risk of foot injuries.

AUTHOR CONTRIBUTIONS

Conceptualization: H.O., A.K., and T.Y.; methodology: H.O.; software: H.O.; validation: H.O., Y.C. and T.Y.; formal analysis: H.O.; investigation: H.O. and T.Y.; resources: H.O. and Y.C.; data curation: H.O., Y.C. and T.Y.; writing—original draft preparation: H.O.; writing—review & editing: H.O., A.K., Y.C. and T.Y.; visualization: H.O.; supervision: H.O. and T.Y.; project administration: H.O. and Y.C.; funding acquisition: H.O. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Effect of self-myofascial release on latent myofascial trigger points in physically active male individuals

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ABSTRACT

Self-massage techniques using foam rollers and massage sticks have gained popularity for enhancing athletic performance and recovery. This study evaluated the effectiveness of self-myofascial release (SMR) on latent myofascial trigger points (L-MTrPs) in the hamstrings and quadriceps. Fifty participants aged 19 to 25 were assessed for pain pressure threshold (PPT) and L-MTrPs. From this group, 30 participants with the lowest PPT values were randomly assigned to either a control group or an SMR group. The SMR group received foam rolling treatment twice weekly for six weeks, while the control group received no intervention. PPT and ultrasonographic measures were recorded before and after the treatment period. A one-way repeated measure design was used as a statistical technique to compare the repeated effect of the SMR intervention on L-MTrPs. Results showed significant improvements in PPT for the SMR group compared to the control group, indicating a reduction in pain sensitivity. The SMR group experienced marked improvements from baseline to the sixth week. These findings suggest that SMR can effectively reduce pain associated with L-MTrPs, potentially through changes in tissue properties, improved blood flow, or neurological effects. Despite promising results, the mechanisms behind these effects are not fully understood, and the study's findings need further validation. Additional research with larger sample sizes, standardized methods, and placebo controls is necessary to confirm the benefits of SMR and refine treatment protocols. Future studies should also explore optimal treatment parameters and the impact of SMR on other body regions and types of trigger points.

Keywords: Sport medicine, Athletes, Foam rolling, Myofascial pain syndrome, Musculoskeletal, Self-myofascial release.

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INTRODUCTION

During the past two decades, active self-massage treatments using by various instruments such as, foam rollers, roller massagers, sticks or balls, have rapidly gained popularity amongst elite and recreational athletes (Biscardi & Stroiney, 2021; Ferreira et al., 2022). It is well-respected in the strength and conditioning field for its ability to enhance the effectiveness of training and competition preparation, as well as for speeding up recovery after exercise (Behm & Wilke, 2019; Wiewelhove et al., 2019). Research evidence suggests that foam rolling improve myofascial health (Hendricks et al., 2020). Fascia plays a large role in musculoskeletal dynamics (Das et al., 2024). Healthy fascia leads to better quality of movement, while restricted fascia becomes a site of tension, diminishing functional movement capacity (Ajimsha et al., 2020; Anwar et al., 2024). The common fascia disorder is latent myofascial trigger points (L-MTrPs) (Das & Jhajharia, 2022; Wilke et al., 2018), these trigger points (TrPs), can be develop though any kind of physical activity (Benito-de-Pedro et al., 2019; Das, Jhajharia, Shukla, et al., 2023), and these MTrPs can negatively affect the sports performance as well as daily life activities (Das, Jhajharia, Ciocan, et al., 2023; ÖZTÜRK et al., 2022). There is insufficient scientific research elucidating about the effects of "*self-myofascial release*"(SMR) instruments in the treatment of TrPs (Behm & Wilke, 2019; Skinner et al., 2020).

Researchers utilised a multimodal approach that included the application of pressure on TrPs by clinicians and self-administered methods, as well as stretching exercises, and reported improvements in the lower extremity functional scale in six weeks after treatment. Due to the lack of a control group and the confounding of various treatments, it is impossible to draw definitive conclusions regarding the influence of self-release (Grieve et al., 2013). Wilke and his colleagues compared static compression and dynamic foam rolling to a placebo condition when applied to MTrP. In fact, static compression was the only treatment capable of alleviating discomfort (Wilke et al., 2018). Yet, presumably due to the small sample, the difference to the placebo control did not reach statistical significance. The treatment effect of foam rollers, particularly on pressure sensitivity, or pain, is largely unclear (Behm & Wilke, 2019; Hendricks et al., 2020). Most studies carried out rolling interventions according to different parameters, so that the treatment intensity, treatment duration and number of repetitions differed. To date, there is no optimal protocol of a rolling intervention to achieve the best possible results (Wiewelhove et al., 2019). In summary, although signs indicate that self-massage with rolling devices may reduce MTrP sensitivity, but more research is needed in order to definitely substantiate this claim. More importantly, although, manual pressure release seems to improve function and possibly pain, the question arises as to whether these effects actually stem from the release of myofascial adhesions, scar tissue or taut bands(Behm & Wilke, 2019).

Glänzel and his colleagues mention in their article that studies provide low certainty but the effect of SMR and L-MTrPs, therefore researchers recommended to conduct studies on SMR(Behm & Wilke, 2019; Glänzel et al., 2022; Kalichman & Ben David, 2017). According to research evidence myofascial research is still in its infancy; there is no clearance on the duration of treatments and breaks; there is no agreement on the type of roller to be used; there is no clear direction on the force to be applied on the tissue; the speed and frequency of rolling may vary from study-to-study; and the treatment frequency that should be repeated in one session are not always the same. So, due these uncertainties and discrepancies on the treatment methods/protocols and therapeutic effects, some authors affirm that the reported benefits are anecdotal in nature, making evidence-based practice difficult (Dębski et al., 2019). Additionally, to our knowledge, there is no available umbrella review on the effectiveness of SMR instruments on performance and recovery. Therefore, the aim of this investigation is to find out the effectiveness of SMR on L-MTrPs recovery.

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MATERIALS AND METHODS

A randomized control study was conducted to comparing between SMR group and control group, which were afflicted with a L-MTrP in hamstring and quadricep muscles. It was hypothesized that SMR technique would reduce the pressure pain sensitivity, TrPs assessed by means of algometry and ultrasonography.

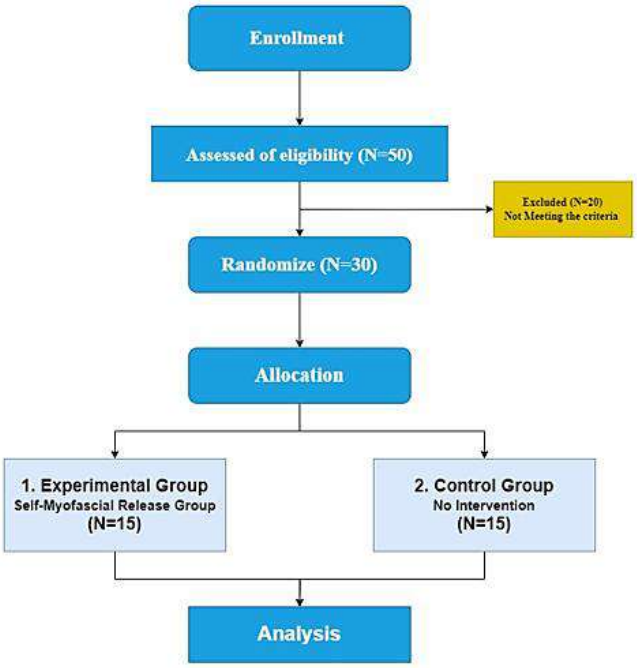

Figure 1. CONSORT study flow chart.

Participation

To execute this study, a total of 50 participants were randomly recruited from the Lakshmibai National Institute of Physical Education, Gwalior. The age of the chosen participants ranged from 19 to 25 years.

Measures

The selected cohort underwent assessments for pain pressure threshold (PPT), and Ultrasonography in lower extremity muscles. Subsequently, 30 subjects were purposefully selected based on their lower PPT values and ultrasonography result. The sample size was determined with the help of the G-power software (Version 3.1.9.7) (Cordeiro et al., 2022). The calculation was done by considering the following criteria: an effect size 0.40 (medium effect), an error probability (1-β) of .95 and an α error probability of .05, the number of groups 1, and number of measures given was 4, an estimated sample size of 15 participants in a group. Therefore, selected subjects were randomly assigned to two different groups: the control group (N = 15), and SMR group (N = 15). Written consent was obtained from the subjects prior to the collection of the necessary data. It was conducted according to the latest version of the Declaration of Helsinki (approval number: 392/1346/27, 22 February 2023).

Procedure

In this present study we used FPX 25 Wagner (FPX 25 Wagner Instruments, Greenwich, CT, USA) pressure algometer to measure PPT(Das, Jhajharia, Shukla, et al., 2023; H. Battecha et al., 2021). Pressure algometers are reliable for evaluating pain thresholds to detect MTrPs (Das, Jhajharia, Ciocan, et al., 2023),

and Samsung Medison V7 ultrasonographic device were used for ultrasonography. All participants were screened for L-MTrP in the Quadricep and hamstring muscles groups (Figure 2). The search, performed under the expert physiotherapist, the TrPs were identified according to Travell and Simons (David G. Simons et al., 1999; Wilke et al., 2018) criteria, which is located near the muscle belly. To confirm the presence of L-MTrPs the participants referred to an expert radiologist who was unaware to the results of the algometric diagnosis. The radiologist has more than 20 years of experience in clinical radiology and 15 years of experience in the ultrasonography of musculoskeletal diseases. L-MTrPS detection was based on the following criteria: (1) palpable taut band, (2) presence of a painful nodule within this taut band, (3) PPT of less than 25 lbs/cm^2 (Cordeiro et al., 2022), and (4) presence of focal hypoechoic (darker) areas with heterogeneous echotexture in ultrasonography (Figure 3). To ensure identical pre- and post-treatment measurements of MTrP sensitivity, each diagnosed MTrP was marked with a skin marker.

Figure 2. Measurement of pain pressure threshold with a pressure algometer.

Figure 3. Ultrasonography of latent myofascial trigger points.

The participants were randomly allocated to two groups, compression of the most sensitive L-MTrP using a foam roller in experimental group (N = 15), and control group with no intervention (N = 15). Randomization was performed by an independent investigator using BiAs 10.04 (Goethe University, Frankfurt, Germany).

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Treatment

The foam rolling (FR) therapy was self-administered using a foam roller, which is commercially available. A foam roller is made of a layer of high-density ethylene vinyl acetate foam over a firm, inner plastic core. During the FR treatment, slow movements were used while constant pressure was put on the muscle's origin and insertion for 90 seconds for each muscle. The treatment was done on one side of the quadriceps and hamstrings. The foam rolling treatment was administered in the following way: Position of the subject: sitting on the floor with the foam roller positioned under the muscle group where TrPs are found. Apply pressure: use the arms to lift the body slightly off the ground and apply pressure (Figure 4) to the foam roller with the lower limb. Roll slowly back and forth over the muscle group, applying pressure to selected areas where L-MTrPs are found. Continue rolling: continue to roll back and forth over the muscle group for 90 seconds for each muscle. Move to other areas: repeat the process on other muscle groups, such as the hamstrings, and quadricep.

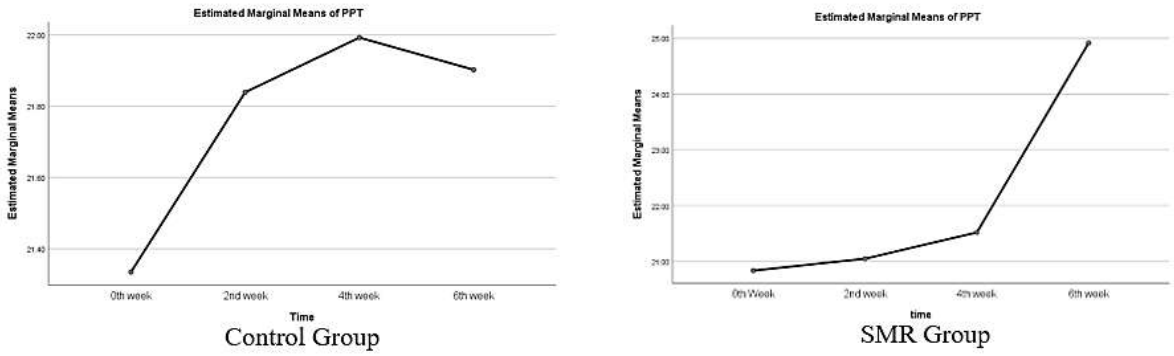

Figure 4. Marginal plot of the control group and SMR group.

Statistical analysis

The statistical analysis was performed using IBM SPSS (version 26.0.0) Mean and standard deviation was used to describe various average of the variables. A one-way repeated measure design was used as a statistical technique to compare the repeated effect of the SMR intervention on L-MTrPs.

RESULTS

The result in Table 1 revealed the mean and Sd of PPT of control and SMR group. From this table it was observed that there were slightly changes in mean value of PPT in control group whereas in SMR group shows major changes in PPT from zero weeks to the sixth week.

Table 1. Descriptive statistics of control and SMR Groups.

		Control Group	**SMR Group**
Duration	N	M ± Sd	M± Sd
0th Week	15	21.33 ±1.48	20.83 ±1.75
2nd Week	15	21.83 ±1.66	21.05 ± 1.57
4th Week	15	21.99 ±1.41	21.51 ± 1.61
6th Week	15	21.90 ±1.26	24.91 ± 0.50

Note. M = Mean, Sd = Standard Deviation, SMR = Self Myofascial Release.

Table 2 is the output of testing sphericity. From this table, it was found that Mauchly's test is insignificant because the *p*-value was .647, which is greater than .05. Since Mauchly's test was insignificant, the sphericity

assumption was not violated. Therefore, no correction was required in the degrees of freedom of the treatment or the error components before testing the significance of the F value. Whereas in SMR group Mauchly's test was significant because the *p*-value was .000, which is less than .05. Since Mauchly's test was significant, the sphericity assumption was violated. This requires corrections to be made in the degrees of freedom of the treatment and the error components before testing the significance of the F value. Since the sphericity exists, therefore, the degree of freedom 1.539, 21.545 instead of 3, 42 would be used. The significance of the F value was tested by means of the p-value, and therefore, the p-value differs in a situation where the Greenhouse – Geisser correction was used (p = .000) and where sphericity was assumed (p = .000). Table 2 also demonstrates the Partial eta squared (η^2), which represents the proportion of variance in the dependent variable that was explained by the independent variable(s) while controlling for other independent variables in the model. The η^2 of control group was 0.241, which is considered a small effect size, whereas the η^2 of SMR group was 0.862, which was considered a large effect size.

Table 2. Mauchly's Test of Sphericity.

	Mauchly's Test of Sphericity		**Tests of Within-Subjects Effects**	
	df	Sig.	Corrected df	Partial Eta Squared
Control Group	5.42	0.647	5.42	0.241
SMR Group	5.42	0	1.539, 21.545	0.862

Note. Df = degree of freedom.

Table 3 shows the pairwise comparisons for different weeks. The difference between the group means of the 0th week and 2nd week, 4th week, and 6th week were insignificant because of the *p*-values were greater than .05. Whereas SMR group shows 0th week, 2nd week, and 4th week was insignificant as the *p*-value was greater than .05, whereas 0th week and 6th week were significantly different as the *p*-value was less than .05. that indicate foam rolling treatment improves the PPT after 6th week of training.

Table 3. Pairwise comparisons.

		Control Group			**SMR Group**		
(I) Time	(J) Time	Mean Difference (I-J)	S. E	Sig.a	Mean Difference (I-J)	S. E	Sig.b
0th week	2nd week	-0.5	0.18	.08	-0.21	0.11	.53
	4th week	-0.65	0.22	.06	-0.68	0.22	.05
	6th week	-0.56	0.19	.06	-4.07*	0.4	.00
2nd week	0th week	0.5	0.18	.08	0.21	0.11	.53
	4th week	-0.15	0.16	1.0	-0.46	0.15	.06
	6th week	-0.06	0.21	1.0	-3.86*	0.35	.00
4th week	0th week	0.65	0.22	.06	0.68	0.22	.05
	2nd week	0.15	0.16	1.0	0.46	0.15	.06
	6th week	0.09	0.2	1.0	-3.39*	0.34	.00
6th week	0th week	0.56	0.19	.06	4.07*	0.4	.00
	2nd week	0.06	0.21	1.0	3.86*	0.35	.00
	4th week	-0.09	0.2	1.0	3.39*	0.34	.00

*Note. Based on estimated marginal means. *. The mean difference is significant at the .05 level. b. Adjustment for multiple comparisons: Bonferroni.*

Figure 4 shows that there was no improvement in PPT in general over time due to no intervention because the *p*-value between the 0th week and to 6th week is greater than .05, which indicates there was no significant increase in PPT. Thus, based on the sampled data and marginal plot, it may be concluded that there was no significant improvement in the PPT.

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DISCUSSION

The present study investigates the effect of six-weeks of SMR training on L-MTrPs recovery on selected muscles. The SMR technique demonstrated a significant improvement in muscular PPT in the experimental group following repeated SMR interventions, whereas the control group showed no improvement. This study indicates that a six-week regimen of SMR, performed twice weekly for 90 seconds per session, significantly enhances the PPT in selected muscles. The underlying mechanisms of the effects of the rolling intervention are not fully understood and are still discussed(Behm & Wilke, 2019). Possible mechanisms may be subject to mechanical and physiological, neurological and psychological influences (Skinner et al., 2020). In regard to the mechanical and physiological influence, it is assumed that rolling treatment can change the properties of the tissue, such as adhesions and hardening, as well as the water content and blood circulation (Hendricks et al., 2020; Martínez-Aranda et al., 2024; Wilke et al., 2020). For example, it has been shown that after a rolling treatment on the thigh, the blood flow increased locally by around 70 % and that the supply to the muscle fibres could be improved (Hotfiel et al., 2017). However, whether the forces on the muscle myofascial release techniques are actually sufficient to dissolve myofascial adhesions and hardening is critically discussed (Behm & Wilke, 2019; Chaudhry et al., 2008). It appears that the surface of the foam roller is too wide to generate the necessary pressure to effectively alter fascia (Behm & Wilke, 2019).

A three-dimensional mathematical model was used to determine how great the mechanical forces of manual therapy would have to be to deform fascia. According to the results of the calculations, dense tissue, such as the plantar fascia and fascia lata, can only be deformed by forces that lie outside the physiological limits of humans (Chaudhry et al., 2008). Although the pressure from the foam roller does not appear to be sufficient to change the properties of the tissue, it could possibly have an effect on the mechanoreceptors located in the skin. These mechanoreceptors may include the Ruffini corpuscles, which are stimulated when stretch and shear forces occur and could inhibit the activation of the sympathetic nervous system. Perhaps this could lead to a global relaxation of the musculature and result in a change in the PPTs (Behm & Wilke, 2019). On a neurological level, it is assumed that the analgesic effect of rolling treatment is triggered by descending pain modulation. One phenomenon of endogenous pain inhibition that could possibly explain the acute hypoalgesic effect of a rolling treatment is conditioned pain modulation (CPM) (Skinner et al., 2020). CPM is based on the principle that a painful stimulus, such as rolling on a foam roller, could inhibit the pain sensitivity of subsequent stimuli via central nervous system processes (Nuwailati et al., 2022). Other myofascial treatments have been investigated with regard to an analgesic effect and CPM: For example, painful massages showed higher PPTs compared to painless massages and were associated with an improved response to CPM (Wilson et al., 2021). For myofascial trigger point treatments, it was found that there was a correlation between the analgesic effect and CPM (Szikszay et al., 2024).

The determination of remote PPT measurements is suitable for the assessment of systematic (central) mechanisms (Naugle et al., 2012). In this study, various authors (Cheatham et al., 2017; Cheatham & Baker, 2017; Cheatham & Kolber, 2018; Young et al., 2018) showed that rolling treatment resulted in a change in remote PPTs on the non-treated side in a pre-post comparison. Based on these results, it could be argued whether the PPTs were possibly altered by the influence of the central nervous system, for example by CPM. However, the meta-analysis presented could not confirm this hypothesis, as no comparison could be made between the rolling interventions and control groups for remote PPTs (Behm & Wilke, 2019). However, the explicit psychological effects of rolling interventions have not yet been investigated. Other myofascial treatments, such as massages, appear to have an effect on the psyche and correlate with reduced stress and increased well-being (Dakić et al., 2023). Furthermore, studies have shown that the hypoalgesic effect of painful massages was significantly greater when people had a positive expectation during the massage.

In contrast, no hypoalgesic effects were found in people with negative expectations. Interestingly, the expectation towards massages had no influence on pain sensitivity when people received pain-free massages (Wilson et al., 2023).

Therefore, foam roller to treat L-MTrPs offers an intriguing approach to addressing muscle function impairments caused by these points. A major advantage of self-myofascial release (SMR) is that athletes can perform treatments themselves, tailoring them to their individual needs. Although the effects need further validation through larger trials, especially against a placebo control, the relatively short duration of treatment makes it feasible to use during game breaks, such as halftime, and warm-ups. Future research should focus on understanding dose-response relationships, such as the effectiveness of longer or repeated treatments compared to a single session and examine the efficacy of this intervention on other body regions and active myofascial trigger points.

CONCLUSIONS

Using a foam roller to apply dynamic compression to L-MTrPs can help athletes improve muscle function and optimize performance. Our findings suggest that self-myofascial release could play a significant role in treating sports-related pain syndromes. Therefore, further research is necessary to fully understand the potential benefits and mechanisms of self-myofascial release in managing these pain conditions. This research should explore the specific techniques, duration, and frequency of foam rolling required to achieve the best outcomes for pain relief and muscle recovery in athletes. Understanding these factors could lead to more effective and targeted therapies for enhancing athletic performance and reducing injury-related impairments.

AUTHOR CONTRIBUTIONS

All authors have contributed meaningfully to all phases of the project. Dr. Rajdeep Das: Contributed to the study design, development of the intervention protocol, data collection, and drafting of the manuscript. Dr. Anshuman Shukla: Involved in study design, statistical analysis, interpretation of results, and manuscript revision. Dr. Birendra Jhajharia Participated in subject coordination, implementation of the intervention, and data processing. Dr. Cătălin Vasile Ciocan: Supervised the entire research process, contributed to theoretical framework development, final editing and correspondence with the Journal.

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No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Relationships between current and past exercise habits and chronotype and body composition among female university students

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ABSTRACT

The present cross-sectional study investigated relationships between past and current exercise habits, body composition, and chronotypes in female university students. Physical activity, Morningness-Eveningness Questionnaire (MEQ) scores and body composition were assessed in 251 students. Participants were asked about their current exercise habits and in high school habits; each measure was compared among students with consistent exercise habits since high school (EX-EX, n = 84), those with exercise habits only in high school (EX-NO, n = 81), and those without consistent exercise habits since high school (NO-NO, n = 86). The MEQ scores of NO-NO were significantly lower than those of EX-EX and EX-NO, and approximately 40% of NO-NO were of the evening type. However, the MEQ scores were not significantly different between EX-EX and EX-NO. Furthermore, about 51% of NO-NO had body fat ≥30% even with a normal range of body mass index, which was proportionately higher than in the other groups. These results suggest that students who had an exercise habits in high school did not show differences in chronotypes owing to their current exercise habits. However, students without consistent exercise habits since high school may be associated with the late chronotype and higher prevalence of normal weight obesity.

Keywords: Sport medicine, Physical activity, Morningness-Eveningness Questionnaire, Normal weight obesity, Adolescent, Body fat, Muscle mass.

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INTRODUCTION

The university period in a student's life is considered to be an appropriate stage for the acquisition of healthy lifestyle habits, given the transition to an autonomous life (Sempere-Rubio et al. 2022). Nevertheless, universities are also known to facilitate the transition to an unhealthy lifestyle compared to previous school years. A recent review found that although physical activity (PA) declines with transition from high school to university, changes in dietary habits are inconsistent (Winpenny et al. 2020). Furthermore, such a decrease in PA is also reported to be associated with an increase in body weight or body mass index (BMI) (Crombie et al. 2009; Winpenny et al. 2020). Lower PA and/or sedentary behaviour may also be associated with an imbalance in body composition, such as 'normal weight obesity' (NWO) (Wijayatunga and Dhurandhar 2021). In particular, PA among young people in many countries has been reported to be lower in females than in males (Bauman 2009). Indeed, a recent study on female university students found that even those students who had previously exercised regularly had reduced muscle mass if their current PA level (PAL) was low, despite no difference being observed in BMI (Oshita and Myotsuzono 2021) and it is associated with the NWO (Oshita, Myotsuzono and Tashiro, 2022). Therefore, young females, such as university students, are more likely to be physically inactive, making it important to focus on their body composition.

Regarding daily rhythms, individuals exhibit a time orientation, known as the chronotype. The sharp maximum of lateness in the chronotype [i.e., transition to an evening type (ET)] occurs around the age of 20 years (Roenneberg et al. 2004). Although associations between this later chronotype (i.e., ET) and various lifestyle behaviours have been described, an association with PA has also been observed. Recent systematic reviews have found that a later chronotype is associated with less physical activity and more sedentary behaviour (Sempere-Rubio et al. 2022). In addition, a recent study of female university students reported that later chronotype and lower PA were significantly associated with higher body fat and lower muscle mass and suggested the need for chronotype-specific interventions to achieve appropriate body composition (Oshita et al. 2024). Therefore, research on the body composition of university students should focus not only on lifestyle behaviours, but also on their chronotypes.

However, the aforementioned systematic review found that although a chronotype is definitely associated with PA after the mid-20s, the association is weaker in university students and individuals in other age groups (Sempere-Rubio et al. 2022). In contrast, another review reported that an early chronotype [morning type (MT)] exhibited higher PAL and less sedentary behaviour than ET in children and adolescents (Huang et al. 2024). Therefore, association of the chronotype of university students need to be considered not only with current PA but also with past PA. This means that even if students did not have a habit of PA at the university level, if they did have this habit during adolescence, such as in high school, their chronotype may differ from that of those who did not have a consistent PA habit. Furthermore, it may be important to investigate the relationship between such differences and body composition as a health-related factor. Therefore, the present study investigated the relationship between high school and current exercise habits and body composition or chronotypes among female university students.

MATERIAL AND METHODS

Participants

The participants were 304 Japanese female university students aged between 18 and 22 years. Of these, 29 participants who provided incomplete responses in the survey were excluded. In addition, 15 participants with a PA level (PAL) >2.3 were excluded because extremely high PAL may influence the chronotype, as reported in a previous study (Oshita et al. 2024). The remaining 260 participants were divided into two groups:

those with current exercise habits (n = 93) and those without exercise habits (n = 167). Among the participants who did not have current exercise habits, those who also did also not have exercise habits in high school were classified as the NO-NO group (n = 86), and those who had exercise habits in high school were classified as the EX-NO group (n = 81). Among the participants who had current exercise habits, those who had also had exercise habits in high school were classified as the EX-EX group (n = 84). As only nine participants had no exercise habits in high school as well as current exercise habits (NO-EX), they were excluded from the study. For ethical reasons, participants were informed in advance that the survey would be anonymous, that it would be used for the purpose of this study and not for any other purpose, and that any data not used in the study would be discarded. If the results of the survey were to be published, the participants were informed that the data collected would be statistically processed and then published in such a way that individuals could not be identified and that the survey would only be carried out if participants consented. This study was approved by the Research Ethics Committee of Kyushu Kyoritsu University (approval number: 2022–08).

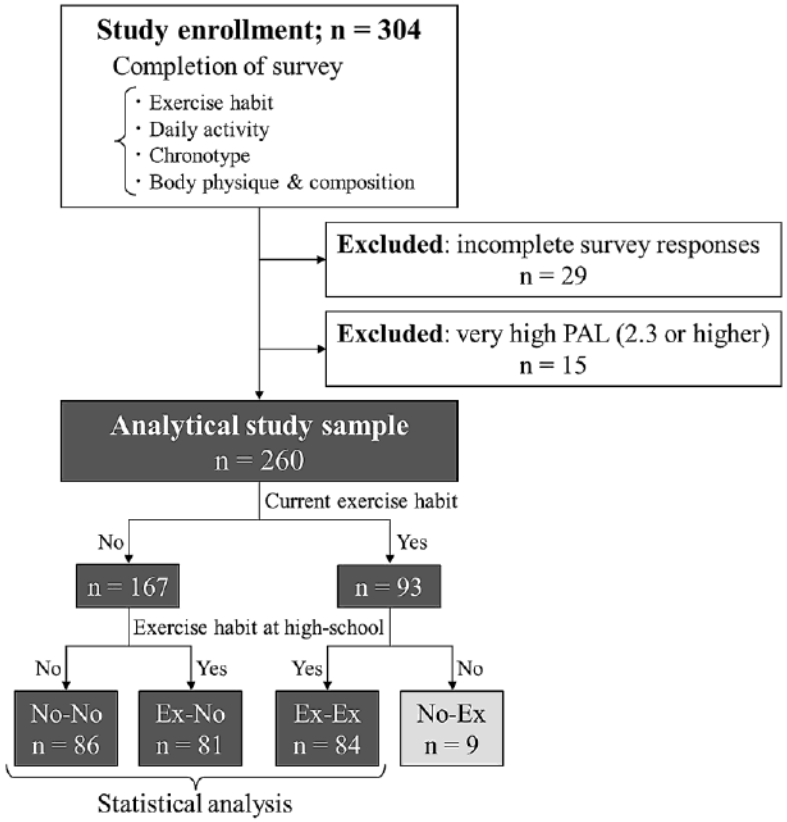

Figure 1. Flow diagram outlining selection of participants for this study.

Questionnaire-based survey and evaluation

Participants completed a questionnaire on their exercise habits, PA status, and chronotype.

Exercise habits and PAL

Two types of questions were asked regarding the participants' exercise habits. Current exercise habits were assessed using the following question: "*Do you exercise at least twice a week for more than 30 minutes each time, excluding sports activities in university classes*". Responses to this question were obtained by selecting 'yes' or 'no'. The participants' previous exercise habits were determined by answering the following question:

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"*When you were in high school, did you exercise at least twice a week for at least 30 minutes at a time, excluding sports activities in high-school classes. Responses to this question were obtained by selecting 'yes' or 'no'.*"

Average daily activity and exercise time on weekdays during the previous month were assessed using a daily activity diary. The PAL of each activity was assessed by calculating the daily average of each classified activity using the product of the energy expenditure index, expressed as a multiple of basal metabolic rate (BMR) and activity time. This method was based on a study that estimated PAL according to the lifestyle of university students based on the "*Dietary Reference Intakes for Japanese people*" (Oshita and Myotsuzono 2021).

Chronotypes

The Japanese version (Ishihara et al. 1984) of the Horne and Ostberg (1976) Morningness-Eveningness Questionnaire (MEQ) was used to assess chronotypes. Individuals exhibiting a chronotype were classified as: definitely MT (score: 70–86) or moderately MT (score: 59–69), neither type (NT; score: 42–58), and moderately ET (score: 31–41) or definitely ET (score: 16–30) (Horne and Ostberg 1976). In the present study, definitively MT and moderately MT were classified as MT, and definitively ET and moderately ET as ET.

Body physique and composition

Body weight and body composition were measured using a body composition analyser (MC-780; Tanita, Japan) and employing the method of multi-frequency bioelectrical impedance analysis. Prior to these measurements, the participants were asked to remain in a seated resting position for 30 min. The participants were asked if they had any urination or bowel movements before the measurements. Subsequently, they wiped their palms and soles with alcohol-free wet wipes to moisten and clean the electrode contact areas, stepped onto the electrode section of the device, and grasped the hand electrodes with both palms. The results of the measurements included body weight, body mass index (BMI), body fat percentage (%BF), fat-free mass (FFM) and appendicular muscle mass (AMM), which were then used for analysis.

Statistical analyses

The mean and standard deviation (SD) of each variable were calculated for all participants. The Kruskal-Wallis test was used to compare variables between groups, and the Dunn-Sidak test was used for multiple comparisons. Additionally, the d-value was calculated as the effect size using Cohen's method. The proportions of participants that showed ET, NT, and MT in each group were also compared using the chi-squared test. The proportions of participants with BMI <18.5 kg/m^2, 18.5–24.9 kg/m^2, and ≥25 kg/m^2 in each group were compared using the chi-squared test. In addition, from the NW-O perspective, a chi-squared test was used to compare the proportions of participants in each group showing a BMI between 18.5 and 24.9 kg/m^2 with %BF of <30% and those with ≥30%. Although the criteria for %BF to assess NW-O vary and are not standardized, many studies have used a %BF of 30% in females (Wijayatunga and Dhurandhar 2021). Additionally, the V value was calculated as the effect size using Cramer's method.

The StatFlex statistical software (ver. 7.0.10; Artec, Osaka, Japan) was used for the aforementioned statistical procedures, with statistical significance level set at $p < .05$.

RESULTS

Measurements for all participants are shown in Table 1 (left), and those for each group are shown in Table 1 (right). Although height and weight were significantly higher in the EX-EX group than in EX-NO and NO-NO

groups, age and BMI were not significantly different among the groups. Regarding body composition, %BF of the EX-EX group was significantly lower (25.5 ± 5.5%) than that of EX-NO and NO-NO groups (28.9 ± 4.9% and 30.7 ± 5.7%, respectively), and FFM of the EX-EX group was significantly higher (42.1 ± 4.3 kg) than that of EX-NO and NO-NO groups (38.4 ± 4.1 and 35.9 ± 3.6 kg, respectively). In addition, FFM of the EX-NO group was significantly higher than that of NO-NO group. These effect sizes were moderate to large (d = 0.59–1.61). These results indicate that the individuals in the EX-EX group had lower body fat and higher muscle mass than those in EX-NO and NO-NO groups, although no differences in BMI were found. PAL was significantly higher in the EX-EX group (2.0 ± 0.2) than in EX-NO and NO-NO groups (1.7 ± 0.2 and 1.6 ± 0.2), with a large effect size ($d \geq 1.31$). Although PAL was significantly lower in the NO-NO group than in EX-NO group, the effect size was small (d = 0.46). MEQ scores were significantly lower in the NO-NO group (44.3 ± 9.5) than in EX-EX and EX-NO groups (49.7 ± 9.2 and 47.6 ± 8.7), but the effect size was not large (d = 0.23–0.36).

Table 1. Means and standard deviations of parameters for all participants and for each group.

	ALL (n = 251)	EX-EX (n = 84)	EX-NO (n = 81)	NO-NO (n = 86)	Kruskal Wallis		Effect size (d)		
					H	*p*	Ex-Ex vs. Ex-No	Ex-Ex vs. No-No	Ex-No vs. No-No
Age (y)	18.8 ± 0.9	18.7 ± 0.6	18.9 ± 0.9	18.8 ± 1.1	1.5	.47	0.19	0.13	0.00
Height (cm)	158.2 ± 5.8	160.5 ± 5.9	158.0 ± 5.2*	156.4 ± 5.6*	18.3	<.01	0.45	0.70	0.00
Weight (kg)	54.3 ± 8.2	56.8 ± 8.1	54.3 ± 7.3	52.3 ± 8.6*	15.0	<.01	0.33	0.54	0.25
BMI (kg/m^2)	21.7 ± 2.7	22.0 ± 2.4	21.7 ± 2.4	21.4 ± 3.2	5.4	.07	0.12	0.23	0.13
%BF (%)	28.4 ± 5.7	25.5 ± 5.5	28.9 ± 4.9*	30.7 ± 5.7*	34.1	<.01	0.66	0.93	0.34
FFM (kg)	38.7 ± 4.7	42.1 ± 4.3	38.4 ± 4.1*	35.9 ± 3.6*†	72.6	<.01	0.86	1.54	0.66
AMM (kg)	17.1 ± 2.8	19.2 ± 2.6	16.7 ± 2.4*	15.5 ± 1.9*†	75.7	<.01	0.96	1.61	0.59
PAL	1.8 ± 0.3	2.0 ± 0.2	1.7 ± 0.2*	1.6 ± 0.2*†	90.6	<.01	1.31	1.68	0.46
MEQ	47 ± 9.4	49.7 ± 9.2	47.6 ± 8.7	44.3 ± 9.5*†	13.1	<.01	0.23	0.57	0.36

*Note. *; vs. EX-EX, †; vs. EX-NO, $p < .05$ (Dunn-Sidak test).*

Table 2 shows the chronotype classification for each group: the percentages of MT, NT and ET were 20.2%, 59.5% and 20.2%, respectively, in the EX-EX group; 11.1%, 60.5% and 28.4%, respectively, in the EX-NO group; and 9.3%, 53.5% and 37.2%, respectively, in the NO-NO group. The percentage of MT was significantly higher in the EX-EX group, whereas the percentage of ET was significantly lower in the EX-EX group and significantly higher in the NO-NO group.

Table 2. Number of participants of morning type (MT), Neither type (NT), and evening type (ET) in each group.

	Chronotype		
	MT	NT	ET
EX-EX	17▲	50	17▼
	20.2%	59.6%	20.2%
EX-NO	9	49	23
	11.1%	60.5%	28.4%
NO-NO	8	46	32▲
	9.3%	53.5%	37.2%

Note. $\chi^2(4) = 9.00$, $p = .06$, Cramer's $V = 0.13$. ▲ and ▼ significantly higher and lower (residual analysis).

Table 3 shows the classification of BMI in each group. Most of the participants in each group had a BMI between 18.5 and 24.9 kg/m^2 (≥78%), and results of the chi-squared test showed no significant differences. Table 4 shows the distribution of %BF for participants in each group with a BMI between 18.5 and 24.9 kg/m^2. The percentages of those with %BF <30% and ≥30% were 90.4% and 9.6%, respectively, in the EX-EX

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group; 59.7% and 40.3%, respectively, in the EX-NO group; and 49.3% and 50.72%, respectively, in the NO-NO group. Although the number of participants with %BF <30% was significantly lower in the EX-EX group, that with %BF ≥30% was significantly higher in the NO-NO group.

Table 3. Number of participants in each group with BMI <18.5 kg/m^2, 18.5–24.9 kg/m^2, and ≥25.0 kg/m^2.

	BMI (kg/m^2)		
	<18.4	**18.5-24.9**	**≥ 25.0**
EX-EX	1 1.2%	73 86.9%	10 11.9%
EX-NO	6 7.4%	67 82.70%	8 9.9%
NO-NO	8 9.3%	71 82.6%	7 8.1%

Note. $\chi^2(4) = 5.82$, $p = .21$, Cramer's $V = 0.11$.

Table 4. Number of participants with body fat <30.0% and ≥30.0% among those with BMI between 18.5 and 24.9 kg/m^2 in each group.

	%BF (%)	
	<30.0	**≥30.0**
EX-EX	66▲ 90.4%	7▼ 9.6%
EX-NO	40 59.7%	27 40.3%
NO-NO	35▼ 49.3%	36▲ 50.7%

Note. $\chi^2(4) = 29.69$, $p < .01$, Cramer's $V = 0.38$. ▲ and ▼ significantly higher and lower (residual analysis).

DISCUSSION

The results of this study showed that the Ex-Ex group had significantly higher PAL than EX-NO and NO-NO groups. Consequently, the EX-EX group had higher FFM or AMM and lower %BF, and the effect sizes were moderate to large. This is consistent with a previous study showing that even if female university students had a habit of exercising in high school, they had lower muscle mass if their current PAL was low (Oshita and Myotsuzono 2021). Therefore, these results suggest that current exercise habits are a contributing factor to appropriate body composition. In contrast, neither the participants in the NO-NO nor in EX-NO groups had current exercise habits, and although there was a significant difference in PAL, the effect size was small. However, FFM and AMM were significantly lower in the EX-NO group than in the EX-EX group and the effect size was moderate. A study on women aged 18-28 years reported that exercise habits at 7 years of age or older had a positive effect on muscle mass (Ayabe et al. 2019). In the present study, the NO-NO group did not have the opportunity to consistently gain higher muscle mass from the past to the present, which may have resulted in the differences in FFM and AMM between the NO-NO and EX-NO groups.

Regarding association with chronotypes, no significant differences in MEQ scores were found between the EX-EX and EX-NO groups. A previous review had shown an inconsistent relationship between PA and chronotypes in university students (Sempere-Rubio et al. 2022). The present study also showed that university students who had exercised in high school (i.e., the EX-EX and EX-NO groups) did not differ in chronotypes according to their current exercise habits. In contrast, both the NO-NO and EX-NO groups did not have current exercise habits, although the NO-NO group had significantly lower MEQ scores. A relationship between lower PAL and later chronotype has also been observed in children and adolescents (Huang et al. 2024). Therefore, the specific chronotype (e.g., ET of MT) shown owing to previous PA may

not be fully modified by current PA. This may explain why the relationship between the chronotype and PA observed in the mid-twenties is not consistent in university students.

As the current study is a cross-sectional study, the causal relationship between PA and chronotype is not known. Therefore, it is not known whether exercise habits influence an individual's morning chronotype or whether the morning chronotype has an advantage in establishing one's exercise habits. A previous study on circadian phase (not chronotypes) showed that exercise in young adults with ET advanced the circadian phase regardless of the time of exercise (Thomas et al. 2020). Furthermore, light exercise in the morning in inactive adolescents with a later chronotype (Lang et al. 2022) and a gradual earlier exercise schedule among them (Richardson et al. 2017) have been suggested to advance the circadian phase. Although the mechanism between PA and circadian rhythm is not known, moderate exercise during the day has been suggested to promote adjustment of circadian rhythm, similar to stimulation with light (Hower et al. 2018). Therefore, depending on the time of exercise, exercise habits may advance their circadian phase, making them more likely to adapt to a morning-oriented culture.

The participants in the NO-NO group had lower MEQ scores, with approximately 40% of them being ET in this study. Although the present study focused on exercise habits, previous studies have reported an association between ET and other lifestyle behaviours. In terms of diet, an individual of ET was more likely to skip breakfast or consume fewer calories during breakfast, while consuming more calories during dinner and snacks in the afternoon or at night (Mazri et al. 2019; van der Merwe et al. 2022; Baldan and Ozcelik-Ersu 2024). Furthermore, irregular meal patterns were also found to be associated with later chronotype in university students (Nishimura et al. 2023). An association between chronotype and sleep problems has also been reported. Social jetlag (SJL) is the difference in the midpoint of sleep between work/school days and free days; a later chronotype has been found to be associated with an increase in SJL, and females may be at a higher risk of developing adverse health symptoms because they have a higher SJL than males (Kodama et al. 2019). Furthermore, a recent report has shown that an increase in SJL is associated with lower PA in female Japanese students (Shibata et al. 2024). Although the present study found no significant difference in exercise habits based on BMI classification, more than half of the participants in the NO-NO group with normal BMI had a high %BF (≥30%). These findings indicate that individuals who did not have exercise habits throughout their past may have an imbalance in the body composition not only due to energy expenditure from physical activity, but also due to lifestyle differences because of them being ET. Therefore, individuals with no exercise habits in the past may require lifestyle modification according to their chronotype to achieve appropriate body composition.

This study has some limitations. First, this is a cross-sectional study, and future longitudinal studies are needed to investigate whether changes in PA are associated with changes in chronotypes. In particular, it would be interesting to evaluate in what way the chronotypes change when individuals with no previous exercise habits later develop an exercise habit. Although the NO-EX group was excluded from the analysis in this study because of the small number of participants, future studies should include this type of participants. Second, the exercise habits examined in this study did not investigate the time of day at which participants exercised. A previous study has suggested that evening exercise in MT delays the circadian phase (Thomas et al. 2020). Furthermore, another study has reported that evening exercise in adolescents may delay the circadian phase (Richardson et al. 2017). However, a study on sleep patterns indicated that evening exercise may advance sleep onset and wake time, and that there is no association between sleep duration or sleep quality and pre-sleep exercise (Kahn et al. 2021). Therefore, although the relationship between the time of exercise and sleep-wake cycle may be weak, future studies may elucidate the relationship between exercise habits and chronotypes, including the time of exercise. Finally, the present

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study was based on a questionnaire; however, sleep-wake rhythms and physical activity should be assessed using objective methods (e.g., using an activity monitor).

CONCLUSION

This study investigated the relationship between exercise habits in university and high school and chronotypes and body composition among female university students. Participants with exercise habits in high school and university had significantly lower %BF and significantly higher %FFM than those without exercise habits in university. Although participants without exercise habits in high school and university had significantly lower FFM than those with exercise habits in high school only (without current exercise habits), there was no significant difference in %BF. Furthermore, more than half of the students without consistent exercise habits had a %BF ≥ 30% despite a normal BMI range, which accounted for a significantly higher proportion. Regarding the chronotypes, students with consistent exercise habits showed a significantly higher MT and significantly lower ET. However, students without consistent exercise habits had significantly lower MEQ scores than the other groups; approximately 40% were ETs, accounting for a significantly higher proportion. These results indicate that female university students with consistent exercise habits from high school were fewer in the ET category. These results suggest that current and past exercise habits of university students are related to specific chronotypes (e.g., ET or MT), and that fewer students with consistent exercise habits in high school belong to the ET category, while more students (approximately 40%) without consistent exercise habits belong to the ET category. Furthermore, students without consistent exercise habits were more likely to be normal-weight obesity.

AUTHOR CONTRIBUTIONS

IY and OK designed this study and interpreted the data. IY, OK, SK, MR and NK collected and analysed the data. IY and OK was a major contributor to writing the manuscript, and SK, MR and NK substantively revised it. The authors read and approved the final manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Smart physical education: Integrating flipped classroom with IoT and android for enhanced learning

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ABSTRACT

This study aims to develop and test the effectiveness of Internet of Things (IoT) and Android-based applications in flipped classroom for physical education in elementary schools. This technology is expected to improve students' basic movement skills, physical abilities, interactive skills, behaviour, self-confidence, and preschool perspective. This study uses Borg and Gall research and development (R&D) methods with two main objectives, namely product development and effectiveness testing. The sample consisted of 197 students in Grades 4, 5, and 6 who had previously been tested for digital literacy. Validation is carried out by two experts in the field of credible materials and media, consisting of lecturers and software developers. The validation results show this app gets an assessment of "*very good*" from material experts and "*good*" from media experts. Trials on students and teachers showed "*very good*" results in the display, content and learning aspects. Effectiveness testing using an Independent t-test showed significant improvements in students' Pulse and cognitive variables. In conclusion, This IoT and Android application is valid and effective in flipped classroom, improving material access, interaction, collaboration, and objective assessment. Further research is suggested to compare the effectiveness of learning between IoT-based flipped classroom and Android with traditional methods or flipped classroom without additional technology.

Keywords: Physical education, Flipped classroom, Internet of things, Android.

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INTRODUCTION

Physical education today faces two main problems. One of them is the limited interaction between students and teachers, because in many colleges and universities, this course is usually only held once a week, so the opportunity to communicate and interact directly is very limited. (Hernández et al., 2019; Vagle et al., 2023). Flipped learning has been trending in recent years, but there is a lack of research in physical education that integrates this system. Yet results have shown a positive impact on motivation, learning and motor skill development (Osterlie et al., 2023; Østerlie et al., 2023; Aliriad et al., 2024). The model consists of analysis, design, development, implementation and evaluation stages, with a focus on learner analysis, curriculum analysis, cooperative instructional design and physical activity support strategies (Yip et al., 2023). Research on the design and implementation of digital and in-class instructional components is needed to guide best practices (Zhu et al., 2023). In the classroom, students and teachers use more forms of communication and discussion. Students learn on their own through teaching resources designed and planned by teachers, such as teaching videos, micro-classes, and open online courses.

The Internet of Things-based technology acceptance learning management framework in physical education helps set clear goals, organize resource allocation, and carry out effective team management (Che et al., 2023). IoT technology and physical education can also help improve students' basic movement skills, physical abilities, interactive skills, behaviour, self-confidence, and preschool perspectives (Lei et al., 2021). IoT in physical education can improve knowledge and performance, optimizing the learning process.

Android-based tools have been developed to help physical education teachers collect data on students' skills related to physical fitness (Santoso et al., 2023). Students have shown positive perceptions of using Android-based learning media in physical education, with familiarity and using videos and images for learning purposes (Haryanti et al., 2021) various diversity of benefits of applying Android in learning.

Indonesia has a diverse signal distribution. However, teachers must remain integrated with technology. The use of the internet integrated with Android is rare in Indonesia. Internet is accessed with an easy signal, and the Android system places with limited signals. In 2022 and 2023, researchers produced a needs analysis of internet and intranet "*fusion*" in physical education learning. This research aims to overcome the weaknesses of the internet with the Android system and vice versa *(reciprocal).*

Some limitations of previous research (Martin et al., 2015) were the limited assessment resources available to physical educators and the difficulty in constructing creative assessments due to program and curriculum variations. Assessments can only be accessed when the signal is stable. (Chen & Dong, 2022) need for clarity in evaluation objectives, indices, and content. There needs to be more diversity and authority in evaluation methods and results, which will be refined in this study. (Sigit et al., 2022) Quota and signal quality are expensive, using an Android base, and the price is costly, as well as internal factors such as student motivation and learning environment—lack of transfer between learning and actual teaching situations (Slingerland & Weeldenburg, 2019). Assessments at lower levels of Miller's pyramid have higher reliability but lower validity. Some of the studies above used a single medium. The learning media was tested on conventional learning. No press or multimedia has been tested on flipped learning. Some studies found some obstacles, such as culture, sample, assessment, and evaluation of learning. This research is novel, namely the use of two media fused into one: the Internet of Things and Android. Then, the effectiveness trial will be carried out on learning set up by Flipped Learning.

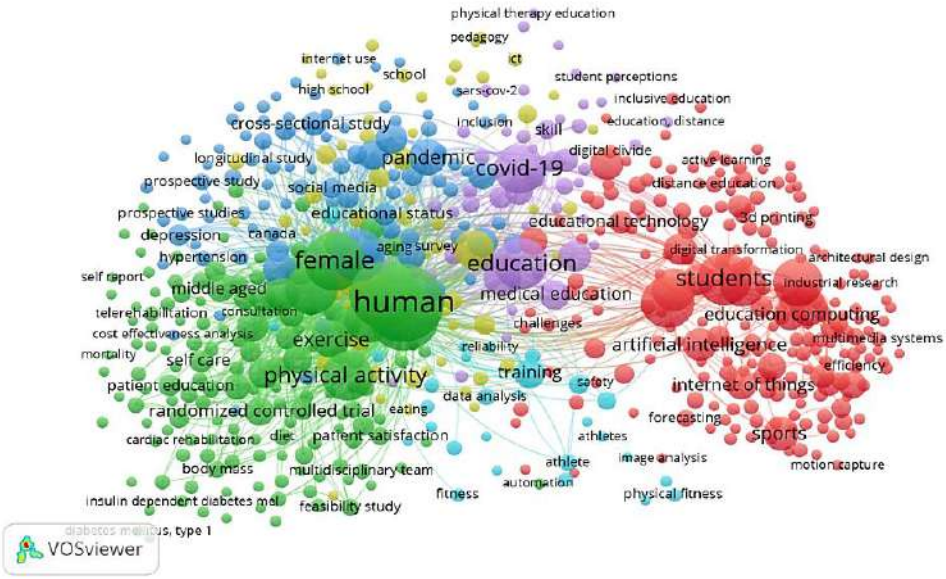

Figure 1. Bibliometric research topics supporting *State Of The Art.*

The researcher strengthened the novelty by analysing research on Scopus, as many as 1000 articles, to find research trends that are often researched. The keyword typed is physical education technology. Researchers analysed from 2021-present. Internet use, the digital divide, educational technology, multimedia systems, the internet of things, flipped learning, and Android base are minimally researched topics in physical education research. This research is expected to pioneer the effectiveness of using two media in a flipped learning class.

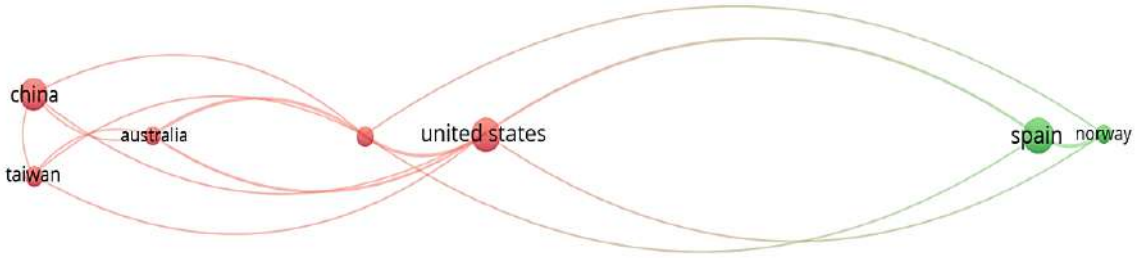

Figure 2. Distribution of researcher countries.

The author then analysed the Scopus database with the keyword flipped learning in physical education learning. It was found that countries that often research this are America, Spain, Taiwan, Australia, and China. Meanwhile, Indonesia rarely carries out this research. This research aims to produce IoT and Android products through developing, validating, and pilot testing flipped learning in physical education.

This study offers novelty by integrating the flipped classroom model into physical education, which has not been widely applied in this context. The main innovation lies in the use of Internet of Things (IoT) technology to collect student performance data through wearable devices, as well as the development of an Android application to support learning and data management. The research process also includes validation and pilot study stages, ensuring that the approach is not only theoretically designed but also empirically tested for effectiveness and practical implementation in the physical education context.

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METHODS

Research design

The sample of this study amounted to 197 elementary school students. The samples selected were grades 4, 5, and 6. Teachers tested in advance regarding "*digital literacy*". The research and development procedure consists of two main objectives, namely: (1) product development and (2) testing the effectiveness of the product in achieving the objectives. This development model is descriptive because the procedures used describe the steps and are used to make the software product "*amongrogo*."

Collection of research instruments

This product consists of two main developments, namely the Internet and Android, which are united in one whole. The first stage in this development is a needs analysis, which begins with a survey of Physical Education (PE) learning through several questions related to the learning process and the interest of teachers and students in applications that can facilitate learning. At this stage, an analysis of the use of gadgets by teachers and students was also carried out, as well as an analysis of literature from reliable sources such as Scopus, WoS, and Sinta. Furthermore, an assessment of the problems faced, early product development in the form of learning media applications, analysis of product objectives and characteristics, identification of content sources for product design, and setting the stages of product manufacture.

The next stage is Software Planning and design, where we design and determine the classification of the results of the needs analysis, including the layout and appearance of the application. The results of these steps are consulted with physical education experts and media or informatics engineering experts to ensure the development of coding applications according to user criteria. After the planning and design is completed, validation is carried out by media and material experts who have credibility in their fields, involving two experts, namely lecturers and software developers.

After validation, field trials are conducted aimed at getting feedback and revising the product. These trials were conducted on a small and large scale, where the small-scale trial involved two classes of Upper Primary School students, while the large-scale trial was conducted in eight classes of four primary schools. The subjects involved in this trial were teachers and students. After the trial process, revisions are made based on expert input as well as test results to improve product quality before widespread use. The final stage of this development is the refinement of the product into an application based on the Internet of Things and Android, which will be equipped with a manual for users. Features that will be embedded in the application.

The output of earlier research, which was restricted to material, was the creation of websites. The website's features will be improved in the next research phase with the addition of random pre-test and post-test questions as well as a separate teacher menu to better control learning in the cognitive, affective, and psychomotor domains. Attendance and presence throughout. The Android application has intranet features for each of these aspects. All of these activities will be put to the test on "*Flipped Learning*" in this study.

Design and implementation of a "*amongrogo*"-integrated, flipped classroom teaching model for physical education. When it comes to teaching design, having standardized, well-defined learning objectives has a direct impact on whether or not the lessons are being taught correctly. In order for students to self-learn in accordance with the goals before learning, correct deviations during the learning process, and conduct self-evaluation regarding the goals after learning, it can guide them step-by-step to the depth of their learning and clarify the level they want to reach. Second, in order to prevent vagueness and abstraction—which will make

the objectives hard for students to understand—objectives should be clear, actionable, and measurable. There are three sections to this flipped learning framework: pre-class, in-class, and post-class.

In the pre-class phase, the students are grouped into small groups based on their real-world circumstances, and the expected learning goals are established for each group. In accordance with the syllabus, the physical education teacher gathers teaching videos—brief films lasting three to five minutes—pictures, teaching materials, and documents on the subject matter and uploads them to "*amongrogo*." While teachers post pertinent questions on the platform and permit students to participate in online discussions in groups, students download the instructional and learning materials on their own. The instructor employs various types of "*questions*" throughout the discussion to enable students to interact online in accordance with the questioning principle. Questions help students think more deeply and develop their understanding of autonomous learning as well as their profound learning ability.

During the in-class phase, students log in after the teacher releases the sign-in via the learning platform. Greetings, announcements of the course objectives and teaching material, and trainee organization are all done by teachers and students. By asking questions about teaching resources or observing how students complete the teacher-created quiz, the platform can assess students' independent learning before class.

The teacher gave clear and precise explanations for the students' collective concerns, and the three groups learned about the issues and uncertainties they had identified. Subsequently, the instructor assigns students to complete warm-up exercises (encompassing both general and sport-specific warm-ups) in physical education class. Following this, representatives from each group are sent to provide an overview of the preclass preview's contents. While other students assess, the teacher only provides guidance and a comprehensive explanation of a portion of the knowledge points. The most crucial aspects of this process are encouraging students to learn actively, helping them to understand key concepts and challenges, and helping them to solidify their knowledge understanding. Following that, students study in groups where team members practice independently and have discussions about the material being covered. Group cooperative learning creates a positive learning environment and helps students identify and resolve issues. In real instruction, the instructor guides, poses questions for the class to respond to, and assists the learners in developing their critical thinking skills.

At the conclusion of the lesson, the instructor sets up activities or games that help students get in better physical shape. Some of these activities include sit-ups, agility games, and re-entry running. We can engage in some relaxing activities after that. Together, the teachers and students will describe the current state of the class, assess if the expected teaching goals have been met, and use feedback to further refine the goals for the following session. The notice of the class's departure is then given.

During the post-class period, the instructor provides open-ended assignments to the students, to which there is no right or wrong response. Pupils analyse the assigned material in-depth on their own, absorb the new information, and ultimately develop higher-order thinking abilities.

Data analysis

The data were processed using descriptive statistics. To complete this study, the researcher also measured the differences in students' pulse rate and cognitive aspects. The data analysed is data that passes the normality and homogeneity test. The average and standard deviation values for each are calculated using SPSS 24. On the pulse and cognitive variables, were tested using the independent sample t-test.

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RESULTS

Before being tested, the application was validated by two experts. The experts are materials expert and media expert.

Table 1. Research development validation.

Variable	Average	St. Deviation	Min.	Max.	Conclusion
Materials expert	4.4	0.17	4.2	4.6	Very good
Media expert	4.1	0.20	4.0	4.5	Good

Source: Developed by author (2024).

Material experts assessed the learning aspects and content aspects. Meanwhile, media experts assessed the appearance and programming aspects. Before the average material experts and media experts provide suggestions for improvement for the perfection of the products developed. The conclusion from the materials expert is "*very good*", while the media expert is "*good*". A "*very good*" rating from a material expert relates to innovation or very adequate quality in learning, while a "*good*" rating from a media expert may indicate there is room for improvement in aspects of communication or information delivery.

Table 2. Pilot testing.

Variable	Average	St. Deviation	Min.	Max.	Conclusion
Student	4.5	0.31	4.1	5.0	Very good
Teacher	4.6	0.32	4.3	5.0	Very good

Source: Developed by author (2024).

Small-scale students tested in one school and large-scale in four schools assessed based on appearance, content and learning aspects. Meanwhile, teachers assessed based on appearance, content and learning aspects. Based on the results of the trial on students and teachers, the results were "*very good*".

Table 3. Description of student pulse rate and cognitive.

Variable		Average	Min.	Max.	SD	Sig. 2-tailed
Pulse	Pulse before	78.4	60	96	8.1	.000
	Pulse after	145.4	115	180	16.5	
Cognitive	Pre-test	57	40	70	2.1	.004
	Post-test	90	70	100	1.8	

Source: Developed by author (2024).

In flipped learning, the teacher has provided the material in advance before learning. The teacher's task during face-to-face is to be a controller. Our trial was conducted on the effectiveness of increasing heart rate and cognitive. In the pulse, students measured by holding their wrists with 30 seconds of calculation. In cognitive, students worked on questions online with 10 questions related to physical education learning. We conducted this trial before and after activities. The statistical results show that there was a significant increase in both components.

DISCUSSION

Based on the results of research that has passed validity tests, pilot testing and effectiveness tests in a flipped classroom environment, several things can be discussed. Flipped classrooms supported by the Internet of Things (IoT) and Android can provide some significant advantages in physical education learning, including:

1. Accessibility of Learning Materials: With the flipped classroom approach, learning materials such as videos, articles, or modules can be accessed online through the Android platform. IoT can extend this access by providing stable and fast internet access in various environments, allowing students to study materials anytime and anywhere.
2. Enhanced Interaction: Through IoT, for example, with motion sensors or wearable devices, teachers can track students' physical activity during practice or physical activity. The data obtained from these IoT devices can help teachers provide more targeted and personalized student feedback and monitor their progress in real-time.
3. Experiential Learning: The integration of IoT in physical education can provide a more immersive and real-world learning experience. For example, using IoT devices to measure physical parameters during training or competition, such as heart rate, pace, or movement intensity, can help students understand the impact of training on their health and performance.
4. Enhanced Collaboration and Communication: The Android platform and IoT-related apps can facilitate collaboration between students and teachers. For example, students can communicate with their teachers directly through the app to discuss learning objectives or get additional guidance.
5. More Objective Assessment: With the data obtained from IoT devices, teachers can objectively evaluate students' physical progress and performance in various aspects of physical education. It can help in decision-making related to lesson planning and developing more focused training programs.

The simulation method of the proposed framework shows that the wearable technology AI-based Internet of Things system (AI-IoTS) enables students to train themselves without the assistance of physical education teachers (Wang, 2022). Internet of Things (IoT) technology and 5G networks enable long-term data collection, real-time monitoring, and improved data transmission efficiency in physical education (Yao et al., 2021). This technology enhances engagement and motivation through gamification and progress tracking, while also improving management and evaluation by recording historical data for in-depth analysis. Additionally, IoT contributes to health and safety by offering health alerts and enabling remote monitoring. The integration of devices and applications into a unified platform also enhances collaboration and communication between students, teachers, and coaches.

Android applications increase student achievement and effectiveness in teaching and learning (Zuhdi & Sukarmin, 2021). Students positively affect learning media based on Android in physical education, with 80% positively affecting it (Haryanti et al., 2021). Using tablets to investigate motion leads to a significant reduction of extraneous cognitive load and greater conceptual knowledge in physical education learning (Becker et al., 2020). Android-based tools can help teachers collect student skills related to physical fitness quickly, effectively, and efficiently (Santoso et al., 2023). Android technology enhances physical education by providing versatile tools that streamline and enrich the learning experience. Through educational apps, students can access instructional videos anytime and boosting engagement and motivation. Android devices also support interactive and multimedia lessons, making fitness education more dynamic. Additionally, data collection and analysis from these devices enable personalized training programs and insights into physical progress. Improved communication through messaging apps and online platforms further supports collaboration between students, teachers, and parents, making physical education more accessible and effective.

Flipped learning has positively impacted affective factors, creating a learning environment that fosters positive emotional dispositions and viewing mathematics as applicable (Lazzari, 2023). In beauty education, flipped learning classes have demonstrated higher learning motivation, immersion, and satisfaction than

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traditional educational methods (Ying & Thompson, 2020). In addition, flip learning based on reverse design has been proven effective in developing permanent understanding and improving students' competence and academic achievement (Joo & Park, 2023). Flipped learning has several benefits in learning. Allows for a flexible learning environment where students can learn at their own pace and participate in activities inside and outside the classroom, leading to increased learning opportunities and achievement (Zhou, 2022). Flipped learning also stimulates student motivation and increases physical activity levels, reducing sedentary behaviour (Yip et al., 2023). Overall, flip learning offers benefits such as increased engagement, motivation, and achievement, as well as increased affective factors and satisfaction in various educational contexts. Flipped learning enhances physical education by reversing the traditional classroom model, allowing students to engage with instructional content outside of class through videos and online resources. This approach maximizes class time for active participation and hands-on activities, as students arrive prepared with foundational knowledge. In PE, this means that theoretical aspects of fitness, nutrition, and sports techniques can be learned at home, while class time is dedicated to practicing skills, receiving personalized coaching, and applying concepts in real-life scenarios. This method fosters deeper understanding, increases student engagement, and enables more individualized attention, leading to a more effective and interactive learning experience.

Flipped learning in PE classes leads to 55% more class time in moderate-to-vigorous physical activity (MVPA) than traditional instruction (Killian et al., 2022). Applying deep learning in flipped classroom design improves students' interest in learning, learning efficiency, and autonomous learning ability in physical education (Huang & Yu, 2022). Maximizing students' time in active physical activity is essential in physical education. Using flipped learning, students can learn concepts, techniques, and strategies at home through videos or reading materials to allocate class time to physical activity fully. It allows students to move more and practice the skills they are learning.

In this study, it was found that students' pulse rate and cognitive abilities increased during learning. The flipped classroom method significantly boosts student engagement in PE, as evidenced by higher levels of emotional, cognitive, and behavioural engagement compared to traditional methods (Wibowo et al., 2024). Enhanced engagement can lead to increased physical activity, which is likely to affect heart rates positively during exercise sessions (Li, 2024). The combination of flipped classrooms and technology not only improves physical fitness but also enhances enjoyment in PE, which can indirectly influence heart rate responses during activities. By combining a flipped classroom model with Internet of Things (IoT) devices and Android applications, the study aims to enhance cognitive engagement and understanding of PE concepts while also monitoring and potentially improving heart rate responses during physical activities. The integration of these technologies is expected to provide a more personalized learning experience, improve students' motivation and focus, and potentially lead to better physical performance and cardiovascular health by closely tracking and adapting to individual physiological data.

CONCLUSIONS

Internet of Things (IoT) and Android fusion products with android are valid and effective for elementary school teachers and students in flipped classrooms. The product is in the form of a website, an android application, and a user manual. Flipped classrooms supported by the Internet of Things (IoT) and Android have significant advantages in physical education learning, accessibility of learning materials, pulse, cognitive, enhanced interaction, experiential learning, collaboration and communication, and more objective assessment. By utilizing the benefits of flipped learning, physical education teachers can create a more dynamic, engaged, and relevant learning experience for their students, improving their concept understanding, physical skills,

and motivation. Future research recommendations include an experimental study comparing academic achievement and student engagement between classes that implement a flipped classroom with IoT and Android support, compared to traditional learning methods or a flipped classroom without additional technology.

AUTHOR CONTRIBUTIONS

Tommy Soenyoto (first author), main researcher, introduction writer/researcher/discussion writer (40%); Adi S. (second author), introduction writer/discussion writer (20%); Agus Darmawan (third author), introduction writer/methodologist (20%); Hilmy Aliriad (four author), introduction writer/discussion writer (10%). Made Bang Ready Utama (five author), introduction writer/discussion writer (10%).

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Transforming physical healthcare training through integration of machine learning and advanced artificial intelligent methods

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ABSTRACT

Mental healthcare and heart disease continues to be a major cause of death worldwide, making it essential to find effective ways to prevent it. Physical activity has long been known to be important for preventing and treating mental healthcare disease, but it is not always clear how much and what type of activity an individual should do. Artificial intelligence (AI) models that can predict a person's risk of mental healthcare disease based on their individual characteristics have become increasingly popular in recent years. In this study, we used AI models to explore the relationship between physical activity and mental healthcare using data from 100 participants that included information about their demographics, medical history, lifestyle, and environment. Our dataset encompasses crucial variables like age, gender, ethnicity, medical history (including heart disease and high blood pressure), socioeconomic status, physical activity (including type, duration, intensity, and frequency), and environmental factors. In this study we predict the mental healthcare and physical activities effect using machine learning (LR, DT, RF, SVM and KNN) and deep learning (CNN, RNN, TabNet, GAN and DQN) models. We leverage cutting-edge analytics, such as machine learning and deep learning, to forecast mental healthcare history based on these factors and examine physical activities and mental health impact on healthcare. Our proposed machine learning method, Random Forest, has demonstrated remarkable accuracy of 88%, while the deep learning model, TabNet-Transform, has achieved an impressive accuracy of 90%. Our Model play key role in enhancing mental well-being and controlling certain psychoneurological disorders.
Keywords: Physical education, Smart healthcare, Artificial intelligent, Mental healthcare, Machine learning.

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INTRODUCTION

Mental healthcare is still a significant health issue globally resulting in numerous diseases and deaths hence stressing the healthcare systems and societies at large. However, mental healthcare has become more common despite advances in medical care and preventions of it. This show the importance of being proactive with regard to risk assessment and management. To minimize the incidence and severity of mental health, it is essential to identify individuals at high risk of suffering from heart disease so as to initiate appropriate treatments for them. Over the years, there has been increasing interest in artificial intelligence (AI) and machine learning (ML) to predict who will have heart disease and stop it (Adedinsewo et al., 2022). Vast and complex medical information may be analysed by using advanced tools like artificial intelligence (AI) and machine learning. They enable customized risk evaluations and therapies for every patient by combining several risk factors. Medical personnel may employ AI-powered prediction models to improve decision-making and resource management. These tools give better patient treatment and general community health results (Shu et al., 2021). AI base tools are helpful for early diseased identification. Physical activities are very important for good health. Predictive analytics and artificial intelligence (AI) have advanced tools to increase physical activity for heart health. Large, complicated data sets may be analysed by AI tools, which can also reveal patterns and insights that are invisible to humans. This enables us to develop extremely precise models that evaluate a person's risk of heart disease. The recommendations for physical exercise can be improved and adjusted over time to sophisticated AI-based algorithms. They provide more effective and long-lasting personalized therapies by gathering real-time data and improving prediction models. These customized methods enhance cardiovascular health (Krittanawong et al., 2018; Lopes, 2021). The main purpose of this study is to determine how well AI models work in predicting and enhancing physical activity levels that promote heart health. We will make use of a small amount of dataset that contains personal information, medical history, daily schedules, and living conditions. We developed model that can precisely identify who is at risk of heart disease based on their unique attributes and level of activity using machine learning and deep learning techniques. We will also examine the relationship between heart health, the environment, and lifestyle choices, as well as how physical exercise influences the risk of heart disease.

This study demonstrates how many risk factors impact the results of heart disease, which infectious disease in our understanding of its causes. These results can be applied to the development of evidence-based strategies for heart disease prevention. Physicians, public health professionals, and everyone attempting to make healthy decisions should all take help form this information. We may make better decisions to maintain our health and lower the global heart disease rate by being aware of these risk factors. Furthermore, the insights offered by this model may be linked into fitness applications and wearables to deliver individualized health advice in real-time. Engaging in physical exercise is not only important for the proper functioning of the heart, but it also contributes a great deal in improving one's state of the mind. Studies indicate that regular participation in sporting activities minimizes anxiety, depression and stress levels as it triggers the production of endorphins and advances brain functionality. Other than that, physical training is also beneficial in the maintenance of cognitive health and may even postpone the aging related brain disorders like depression, anxiety, Alzheimer's and other types of dementia. This relationship between mental health and fitness creates a rationale for activity plans that seek to enhance physical as well as mental endurance. In the advancements of medical field, heart disease is notwithstanding becoming more common; highlight the need for greater preventive measures. Among its many benefits, exercise is essential for both managing and preventing heart disease. Recommend the right sort and intensity of exercise for a particular individual depending on their age, gender, and lifestyle is provocative. It's likely that the way these variables combine to raise cardiovascular risk is not adequately taken into consideration by established guidelines. This grandness the need for targeted, customized therapies that modify physical activity guidelines based on each person's

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unique needs and characteristics. In this article we find that the physical exercise is import for the reduction of heart disease. The contribution of this study is:

- To develop an AI base model to provide personalized mental health and heart disease risk, this is based on individual.
- Developed a comprehensive dataset which encompassed demographics, medical history, lifestyle and environmental factors.
- Compared AI models, and RF and TabNet get very good accuracy, 88% and 90%.
- Guideline and future direction on mental healthcare, physical activities and heart disease.

Related work

Artificial intelligence and heart failure have been the subject of recent research that have explored a range of topics, from risk prediction to customized therapies. The development and testing of AI-based tools to estimate cardiovascular risk is one crucial field (Kagiyama et al., 2019). For example, to properly forecast the likelihood of future cardiac issues, researchers have used machine learning to analyses vast datasets of demographics, medical history, and lifestyle variables (Mathur et al., 2020). These models have outperformed conventional risk assessment instruments, indicating that artificial intelligence may help us better identify vulnerable individuals and create preventative strategies. Some old studies investigate how AI-based therapies might improve heart health and encourage physical activity. In this study author use sensors, wearable technology, and smartphone applications to assess activity, provide real-time feedback, and design individualized workout regimens. According to studies, these treatments successfully improve cardiovascular fitness, promote adherence to exercise guidelines, and reduce risk factors for cardiovascular problems such as obesity, high blood pressure, and raised cholesterol (Krittanawong et al., 2017).

In some recent studies researchers have used artificial intelligence to customize treatment plans for individuals who have already received a diagnosis in addition to predicting and intervening in cardiovascular diseases (Sermesant et al., 2021). AI systems evaluate intricate medical imaging data, including cardiac MRI scans and echocardiograms, to assist in the diagnosis and prognostication of cardiovascular disorders. Artificial intelligence-based decision support systems also assist medical professionals in choosing the best courses of action and maximizing drug schedules according to the unique needs and treatment outcomes of each patient (Vijayakumar et al., 2023). Artificial intelligence has the ability to significantly change preventative cardiac care (Addissouky et al., 2024). It enables more effective treatment plans, tailored treatments, and individual risk assessments. Nevertheless, more study is necessary to verify the long-term advantages, viability, and affordability of artificial intelligence in actual therapeutic settings. Resolving ethical, legal, and privacy concerns associated with the widespread application of artificial intelligence in cardiovascular care is also crucial (Pesapane et al., 2018; Said et al., 2022).

METHOD

Proposed system

The strategy adopted in changing healthcare education enables precise surveillance and forecasting through the use of IoT sensor apparatus, well enshrined machine learning algorithms and the most recent deep learning frameworks. The system is supported by the use of IoT wearables that include; smart wrist lets clothes, shoes and spectacles among others which all help in gathering and monitoring key health and performance parameters in real time. Such devices come with mobile phone connectivity for easy data transfer to the internet and most importantly to the cloud. This connected system allows for monitoring, availability and movement in the system, bringing about interaction between the educators and learners. This system increases the scale and efficiency of operations and provides the healthcare trainers with empirical

evidence-based data for conduct focused on improving the results. A multi-layered architecture that consists of a machine learning algorithm and deep learning models is used to process and analyse the collected data in the system. Initially, the data coming from IoT devices, also referred to as the raw data is fed into a preprocessing stage where noise is removed and relevant features are extracted. In addition, deep learning approach goes a step further to analyse the data of which helps in making predictions accurately as well. This hybrid way of training has ensured that the health care training programs are flexible, effective and allows the provision of support that is individualized to the user. Figure 1 shows the detail steps of data collection and applying ML and deep learning models. This is a major step forward in the use of Artificial Intelligence in health care as well as training and coaching athletes.

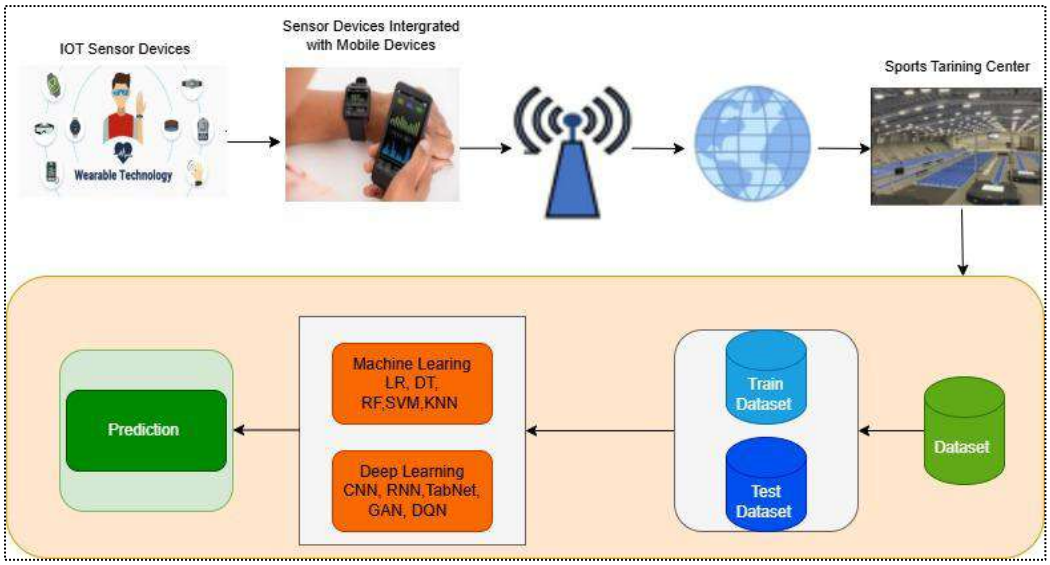

Figure 1. Proposed method flow diagram and collection of sport datasets.

To determine the risk of mental healthcare based on physical activities using your data-set, we recommend exploring a range of deep learning architectures. The data-set contains structured data (like participant demographics and physiological measurements) and sequential data (like physical activity details), a hybrid approach using multiple models may be effective. Here are some machine learning and deep learning models to consider: Logistic regression is a common statistical tool for predicting binary outcomes (e.g., yes/no, true/false). Despite the term regression it's actually a linear model that estimates the likelihood of a specific outcome based on input variables. Logistic regression models data with a sigmoid curve, transforming input values into probabilities. It uses maximum likelihood estimation to determine the weights (coefficients) of the input variables. Notably, it supports both categorical (non-numeric) and continuous (numeric) input variables. It's efficient, easy to interpret, and can handle noisy data. However, it assumes a linear relationship between the input variables and the probability of the outcome, which may not always be accurate (Said et al., 2022).

Decision Trees are a method for supervised learning that don't need any parameters. They can be used to classify and predict data. They work by breaking down the data into smaller groups based on the features and values. Each group is shown as a node in the tree. At each node, the algorithm picks the feature that makes the best split in the data, which makes the subsets as different as possible. Decision Trees are easy to understand which makes them good for knowing how the model makes decisions. But they can easily overfit the data, especially if the tree is too deep (Ville, 2013). Random Forest is a technique that combines many decision trees during training. It produces a result by finding the most common prediction (for

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classification) or the average prediction (for regression) from all the trees. Each tree in the forest uses a unique portion of the training data and a random selection of features, which reduces overfitting and improves accuracy. Random Forests are versatile, resilient, and less affected by noise than individual decision trees. They excel in various tasks like classifying, predicting, choosing important features, and finding unusual data points. However, they can take time to train and need fine-tuning of parameters like the number of trees and their maximum depth (Biau & Scornet, 2015). Convolutional Neural Networks (CNNs) are designed for image recognition and computer vision applications. They automatically learn features from raw pixel data, especially effective for grid-like data like images. By using convolutional layers and pooling layers, CNNs identify meaningful features and spatial relationships within images. This capability makes them ideal for tasks such as object detection, facial recognition, and medical image analysis, where spatial understanding is essential (Albawi et al., 2017; Dey & Salem, 2017; Jain & Medsker, 1999; Liu et al., 2021). In Figure 2, we have the following steps: physical activity data, pre-processing the data in the second and third stages of fracture engineering and fracture encoding, four-step machine learning model selection, training the data, model evaluation, fine-tuning the model, and finally predicting the illness. Similarly, for deep learning, we use the steps.

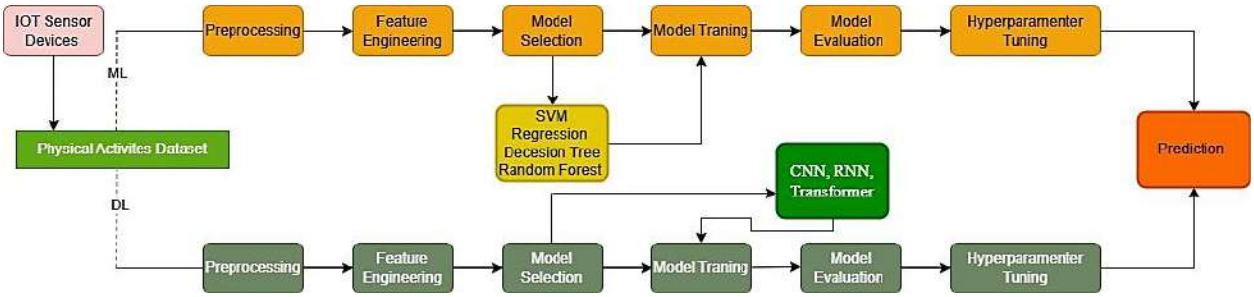

Figure 2. Detail steps of machine and deep learning steps.

Data set

Dataset is available of 100 peoples and provides extensive details on their lifestyle, medical history, demographics, and environmental factors. Their age, gender, socioeconomic background, ethnicity, and medical history (such as heart disease, hypertension, or diabetes) are all included. The dataset also explores lifestyle aspects including food, alcohol use, smoking behaviours, and physical exercise (kind, duration, intensity, and frequency). The dataset analysis reveals that the individuals are from diverse backgrounds. Their ages span a broad age range, from 35 to 65. Because both sexes are equally represented, if necessary, researchers can do gender-specific data analysis. The socioeconomic position and ethnicity data in the dataset enable researchers to investigate possible variations in heart disease risk across different demographic groups. Interestingly, a sizable portion of participants have a history of diabetes, high blood pressure, or heart disease, suggesting that the study population is more likely to experience cardiovascular issues. People differ greatly in their decisions, including what they eat, how much exercise they get, and whether or not they smoke. Their risk of heart disease is impacted by these variations. Additionally, environmental elements such as temperature, humidity, and air quality might affect heart health. In this article we used all features as X columns and predicted Y value is used for heart disease.

Data loading and pre-processing

Data set is in CVS format into a Pandas DataFram, it is a popular Python data processing tool and it is the process of loading data. Participant data including demographics, medical history, lifestyle choices, and heart disease status are often included in this dataset. In the preparation procedures we imputation or removal are

used to deal with missing values. We also used label encoding to translate categorical data (such as gender and ethnicity) into numerical values. For scaling numerical characteristics to a constant range ensures that the predictions of the model are not greatly impacted by a single feature.

Model selection and training

Model selection is very important, in this article; we used machine learning models such as logistic regression, decision trees, random forests, and support vector machines (SVM) for classification problems. These techniques are chosen on the basis of things like efficiency, simplicity, and interpretability. We use deep learning models, such as feed forward neural networks (FNN), convolutional neural networks (CNN), and recurrent neural networks (RNN), for complicated tasks like medical diagnosis. Frameworks like as TensorFlow and PyTorch are used in the construction of these models. They have the capacity to identify complex links and patterns in data. In order to train the model's, pre-processed data is used. The goal variable (y), which denotes a history of heart disease, and the input characteristics (X) are fed into the model iteratively.

Model evaluation

In this article, we evaluate the performance of different models. Model performance is evaluated using a variety of metric. The area under the ROC curve (AUC-ROC), recall, accuracy, precision, and F1-score we used these metrics to assess a classification model's efficacy. The model's performance is displayed in a confusion matrix. It displays the number of times the model recognized an object properly, the number of times it misidentified an object, and the number of times it missed an object. Table 1 and 2 shows us how effectively the model can distinguish between objects and identify any trends in the errors that have been made.

Performance comparison

For compression of performance, we used different performance metrics in this article, we used Accuracy, precision recall and F1-Sscor etc., the optimal model for predicting the history of heart disease is determined by evaluating many models. Accuracy scores and confusion matrices for every model are looked at in order to achieve this. Experts may compare these performance metrics to decide which model is the most effective overall, with the highest sensitivity, specificity, and accuracy. Following equations 1 through 6 are used together with other performance measured (B Padmaja, 2021; Francis et al., 2023; Tiwari & Waoo, 2024; Yapıcı & Topaloğlu, 2021).

$$\mathrm{ACC} = \frac{TP+FP}{TP+FP+TN+FN} \quad (1)$$

$$\mathrm{Precision\ (P)} = \frac{TP}{TP+FP} \quad (2)$$

$$\mathrm{Recall\ (R)} = \frac{TP}{TP+FN} \quad (3)$$

$$\mathrm{F1-Score} = \frac{2*P*R}{P+FR} \quad (4)$$

$$Specificity = \frac{TN}{TN+FP} \quad (5)$$

$$\mathrm{Sensitivity} = \mathrm{Recall\ (R)} = \frac{TP}{TP+FN} \quad (6)$$

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Hyper-parameter tuning and optimization

In proposed method, we have tuned our model by using hyper parameter. Hyper parameter tuning is adjusting a model's parameters to improve performance. To identify the ideal mix, grid search, random search, and Bayesian optimization facilitate effective exploration of various parameters. Models' ability to predict outcomes is improved by adjusting these parameters, which results in estimations of heart disease history that are more precise. Based on a variety of participant characteristics and lifestyle variables, the given code builds models that predict heart disease using machine learning and deep learning approaches. The algorithm attempts to generate strong models for predicting heart disease history through training, optimization, model selection, and data preparation.

Algorithm

Detail steps of proposed algorithm are given, Algorithm 1 used data of physical fitness to anticipate the risk of heart disease. In order to improve modelling and ensure consistency, it begins by correcting missing values in the data and standardizing its characteristics. To enable quick model building and performance evaluations, the data is split into distinct training, validation, and testing sets. Several machine and deep learning techniques are used to train and data throughout the model exploration and training phases. Machine and deep learning models are Logistic Regression, Decision Trees, SVM, K-NN, Convolutional Neural Networks, RNN, and Transformers. Every model is assessed separately and optimized based on pertinent metrics and predicted accuracy. All models, the procedure proceeds to the model assessment phase, when each model's accuracy, precision, and recall are evaluated.

Table 1. Algorithm 1 description.

Input: Physical fitness data **(X)**
Output: Predicted cardiovascular disease **(y) target Label**
Data Pre-processing: Handle missing values and normalize features. $\mathbf{X_{processed}}$ = **Impute(X)** $\mathbf{X_{normalized}}$ **= X−μX / σX** Split the data into training, validation, and test sets. **(**$\mathbf{X_{train}}$**,** $\mathbf{X_{val}}$**,** $\mathbf{X_{test}}$**),** **(**$\mathbf{y_{train}}$**,** $\mathbf{y_{val}}$**,** $\mathbf{y_{test}}$**) = TrainTestSplit (**$\mathbf{X_{normalized}}$**, y)**
Model Selection and Training: Select models for each model in [LR, DT, RF, SVM, KNN, CNN, RNN, Transformer] **M = [LR, DT, RF, SVM, KNN, CNN, RNN, Transformer]** Train each model on the training set: for each model in [LR, DT, RF, SVM, KNN, CNN, RNN, Transformer]: $\mathbf{\hat{y}_{train}}$ **= Train (**$\mathbf{X_{train}}$**,** $\mathbf{y_{train}}$**, m)** $\forall \mathbf{m} \in \mathbf{M}$ Train model on training data
Model Evaluation: Evaluate the performance metrics (e.g., accuracy, precision, recall). **Evaluate(m) = (**$\mathbf{Acc_m}$**,** $\mathbf{P_m}$**,** $\mathbf{R_m}$**,** $\mathbf{F_m}$**,** $\mathbf{S_m}$**, Spm)** Select the best-performing model based on validation metrics. $\mathbf{M_{best}}$ = **argmax Evaluate(m)**
Final Model Testing: Test the selected model on the test set to assess its performance on unseen data. Evaluate model performance using various metrics and analyse predictions. **Evaluate on Test Set = (**$\mathbf{Accm_{best}}$**,** $\mathbf{Pm_{best}}$**,**$\mathbf{Rm_{best}}$**,** $\mathbf{Fm_{best}}$**,** $\mathbf{Sm_{best}}$**,** $\mathbf{Spm_{best}}$**)**
Output: Trained model for predicting cardiovascular disease risk based on physical fitness data (y). **Y =** $\mathbf{m_{best}}$

The model that performs the best during validation is selected, guaranteeing that it can process fresh data efficiently. Lastly, a test set is used to objectively assess the selected model's performance on untested data. Assesses the model's performance using a variety of criteria and verifies the accuracy of its predictions. Through a rigorous procedure, a trained model is created that may use physical fitness data to predict the risk of cardiovascular disease, making it a valuable tool for early identification and preventative healthcare measures.

Experiments

Data analysis was employed in the study to examine the intricate relationships between many variables and the risk of heart disease. Based on a variety of patient factors, prior heart disease was predicted using machine learning techniques. These techniques worked well and correctly classified the patients. The models demonstrated the usefulness of AI for heart disease risk prediction by taking into account variables such as age, gender, socioeconomic position, physical activity, and environmental circumstances. Through machine learning and DL, we can accurately predict the heart disease risk. Results of proposed heart diseased method are given in Tables, 2 and 3.

In this article we found that people who exercise regularly have a lower risk of heart disease. Activities like running, cycling, swimming, and walking can help reduce this risk. Exercise is an important way to keep your heart healthy, and it should be part of any plan to prevent heart disease. The study also found that there are several things you can change about your lifestyle that can help lower your risk of heart disease. Unhealthy habits like smoking, eating poorly, drinking too much alcohol, having a high body mass index (BMI), and unhealthy blood pressure and cholesterol levels are strongly linked to higher rates of heart disease. By promoting better decisions and lifestyle modifications, this highlights the necessity of concentrating on lifestyle-related aspects in health treatments. The study also demonstrates the influence of environment, lifestyle, and demography on cardiovascular health. Healthcare providers and legislators may develop more focused and efficient heart disease prevention and treatment strategies by having a better understanding of these links. Integrating clinical, behavioural, and environmental therapies into all-encompassing strategies to combat heart disease and improve public health. AI-powered prediction and data analytic empower healthcare professionals with more accurate risk predictions and earlier detection. Targeted interventions can result in better cardiovascular health for individuals and communities. A holistic approach prioritizes both personal and public health initiatives to prevent heart disease effectively.

Table 2. Machine learning models for matric measurement.

ML models	Accuracy	Precision	Recall	F-Score	Sensitivity	Specificity
Logistic regression	0.82	0.79	0.85	0.81	0.85	0.79
Decision tree	0.76	0.78	0.72	0.75	0.72	0.78
Random forest	0.88	0.85	0.92	0.88	0.92	0.85
Support vector machine	0.71	0.68	0.75	0.70	0.75	0.68
K-Nearest neighbours	0.79	0.81	0.76	0.79	0.76	0.81

Table 2 displays the performance of five traditional machine learning models used to predict the risk of heart disease using a wide-ranging dataset. Each model is based on a unique approach to classification, employing various algorithms and methods. Logistic Regression stands out with an accuracy of 0.82, highlighting its efficacy in classifying binary outcomes. Its precision of 0.79 and recall of 0.85 indicate its ability to minimize both false positives and false negatives, making it valuable in medical diagnostics where both are important factors. Tree-based models provide different approaches for disease classification. Decision Tree has a slightly lower accuracy (0.76) than Logistic Regression but still maintains a high precision (0.78) and recall

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(0.72). Random Forest performs better, with an accuracy of 0.88, utilizing ensemble learning to combine multiple decision trees. It excels in recall (0.92), efficiently detecting instances of heart disease. Support Vector Machine (SVM) and K-Nearest Neighbours (KNN) have lower accuracies (0.71 and 0.79 respectively), indicating they may not be ideal for this dataset.

Table 3. Deep learning models for metrics measurement.

Deep learning models	Accuracy	Precision	Recall	F-Score	Sensitivity	Specificity
Convolutional Neural Network (CNN)	0.85	0.83	0.88	0.85	0.88	0.83
Recurrent Neural Network (RNN)	0.81	0.79	0.83	0.80	0.83	0.79
TabNet- Transform	0.90	0.87	0.92	0.89	0.92	0.87
Generative Adversarial Network (GAN)	0.78	0.76	0.80	0.77	0.80	0.76
Deep Q-Network (DQN)	0.86	0.82	0.86	0.83	0.86	0.82

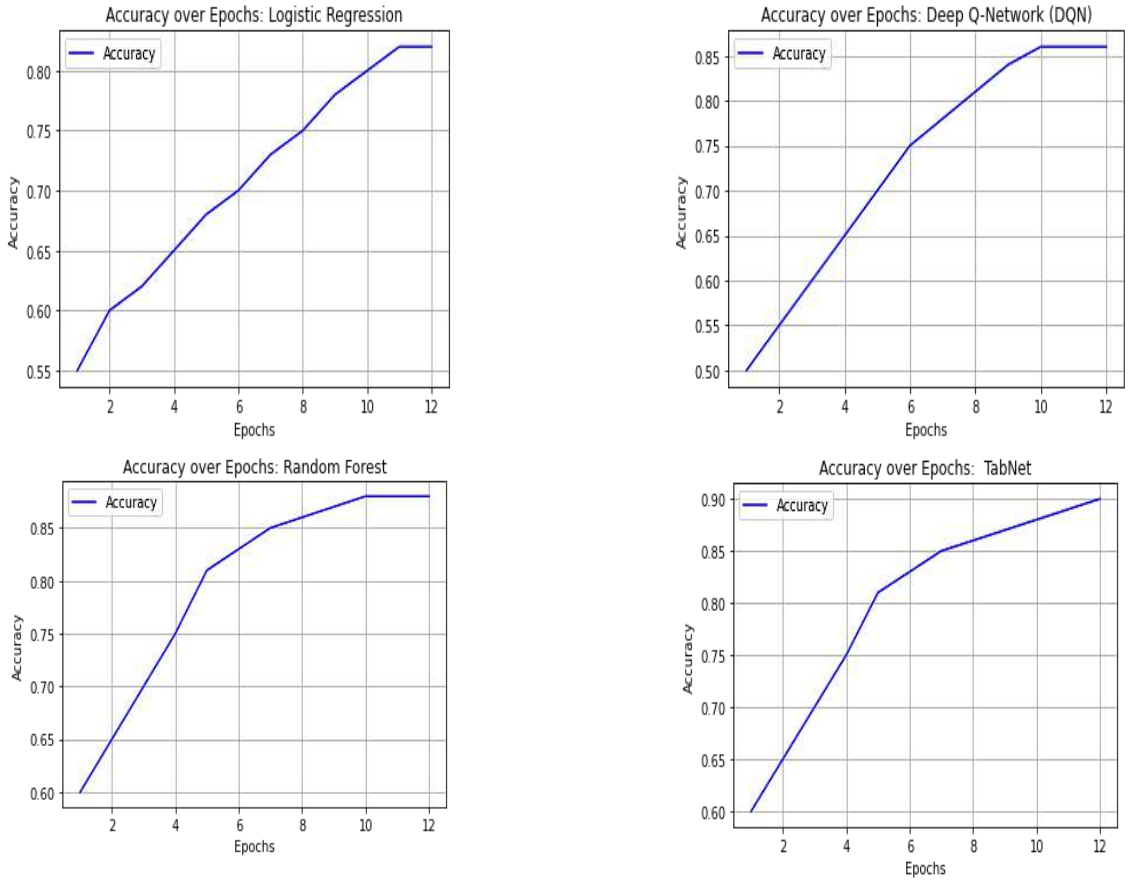

Figure 3: Predicted Accuracy: (a) machine learning models accuracy of logistic regression and model random forest (b) predicted accuracy of deep learning models Deep Q-Network (DQN) and TabNet.

Table 3 shows how well five different deep learning models predicted the risk of heart disease using a large dataset. Each model has a different structure designed to handle different types of data and tasks. The accuracy of the Convolutional Neural Network (CNN) is 85%. This model is best at finding patterns in images and other spatial data, such as medical images or sensor data. The Recurrent Neural Network (RNN) has an accuracy of 81%. This model is best at understanding patterns in time-series data, such as patient histories, because it can process data in order. Among the models, the Transformer surpasses all with an accuracy of

0.90. It effectively captures long-range relationships and context in the data, making it well-suited for both structured and unstructured healthcare data. The Generative Adversarial Network (GAN) and Deep Q-Network (DQN) have slightly lower accuracies of 0.78 and 0.86, respectively. GANs, typically used for synthetic data generation, can also be used for classification with their discriminator component. DQNs excel in reinforcement learning. Choosing the right deep learning model is crucial for achieving the best predictive results in healthcare analytics. The Figure 3 shows a variety of models that can handle different types of data and tasks, highlighting the need for careful selection based on specific requirements.

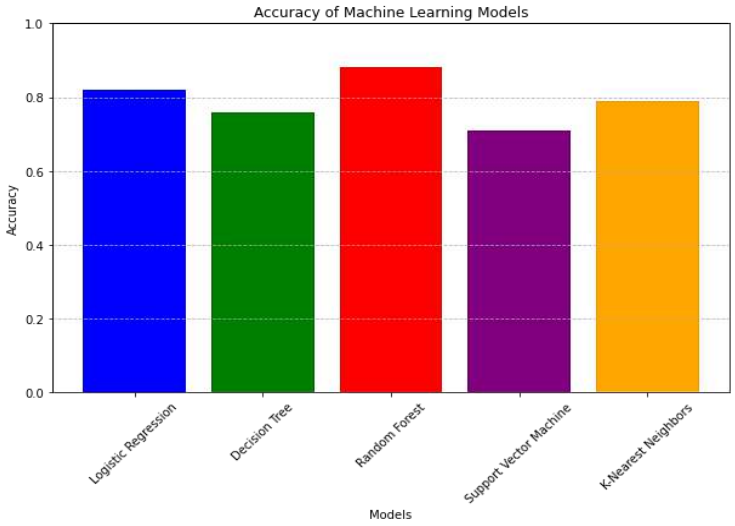

Figure 4. Predicted accuracy of machine learning models.

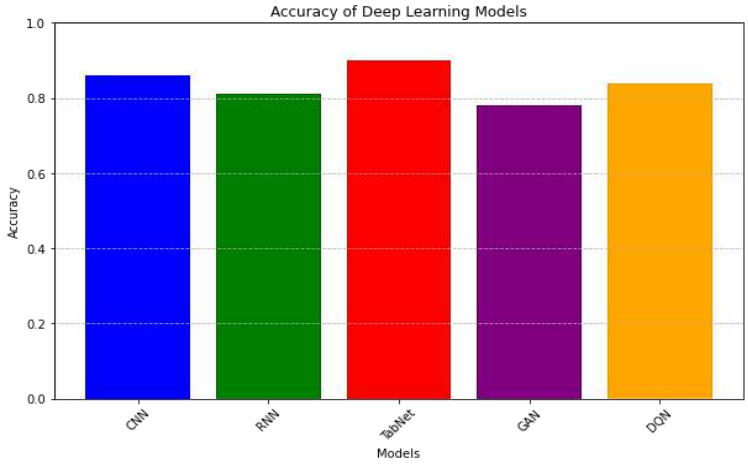

Figure 5. Predicted accuracy of deep learning models.

The TabNet-Transformer versus Random Forest confusion matrix shows strong performance in predicting cardiovascular disease risk. These two classifiers presented high sensitivity and specificity; thus, TabNet has a very high accuracy (0.90), precision (0.87), and recall (0.92) values, as shown. Further, Random Forest has obtained an accuracy of 0.88, precision of 0.85, and recall of 0.92 against confusion matrices. These matrices as well have a considerably low number of false positive counts and false negatives, shown in Figure 4,5. Thus, it will be a reliable classification. Regarding the evaluation of models with ROC curves, both

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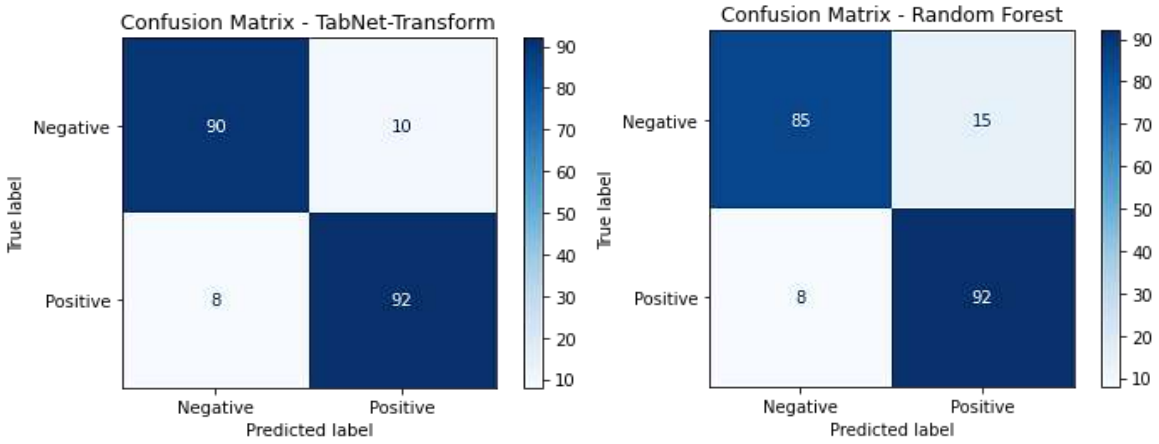

Figure 6. Confusion matrix of highly predicted accuracy model of DL and machine learning.

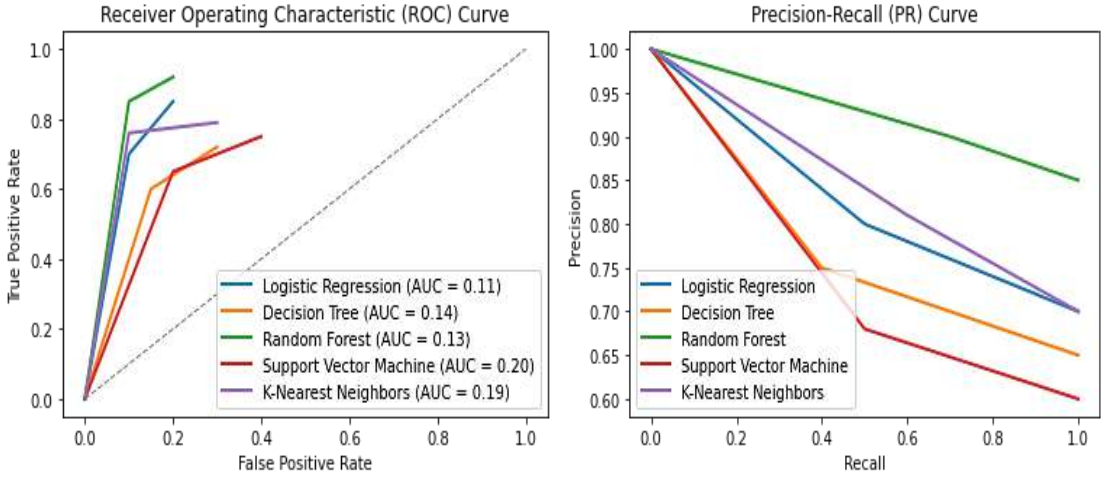

Figure 7. Results of machine learning models, ROC and PC Curve.

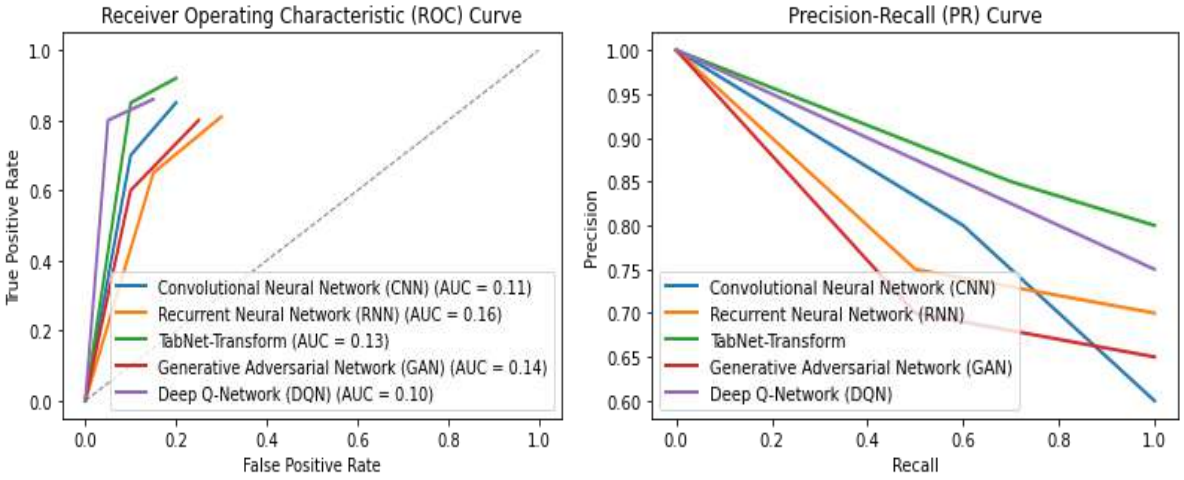

Figure 8. Results of Deep learning models, ROC and PC Curve.

TabNet and Random Forest obtained very high AUC scores, where TabNet performed a little bit better in the AUC part than Random Forest, indicating an excellent ability to discriminate between positive and negative cases of cardiovascular diseases. TabNet again showed its superiority over other models with a markedly better precision and recall in the Precision Recall (PR) curve analysis. This indicates that it effectively minimizes both false positives and false negatives, which is important in medical diagnosis. The ROC and PR curves for machine learning and deep learning models also highlight the excellent performance of TabNet and Random Forest, emerging as two leading candidates for accurate heart disease risk prediction. Figure 6 shows the confusion matrix of random forest and TabNet-Transformer, and Figure 7 shows the detailed comparison of machine learning models, ROC and PR curve and Figure 8 shows the comparison of deep learning models ROC and PR curve.

DISCUSSIONS AND RECOMMENDATIONS

From this study following important points are found, important conclusions from this study point the way for forecasting and avoiding mental healthcare sickness. First it highlights the necessity of a thorough evaluation of heart health that takes into account one's environment, lifestyle, medical history, and habits. These diverse elements contribute to the development of more accurate prediction models, which in turn enable the creation of individualized risk assessments and focused treatments for those who are more vulnerable. The substantial association between physical exercise and a lower risk of heart disease is another important discovery. Regular participation in moderate-to high-intensity physical exercise is associated with a decreased incidence of heart disease, highlighting the preventive role of this activity.

Developing individualized programmers to encourage regular exercise and overcome barriers can greatly lower the incidence of heart disease. Furthermore, our findings indicate that environmental factors such as temperature and air quality can influence heart health, emphasizing the need for more study (B Padmaja, 2021). In order to inform policies that lower environmental hazards and support healthy living circumstances, further study is required to fully comprehend the relationships between environmental variables and heart health. Our conclusions lead us to the following recommendations: 1. Testing prediction models on a variety of populations to increase their utility and accuracy. 2. Giving priority to programmers' that promote physical exercise on a personal, social, and legislative level. Urban planning and the implementation of tested policies are critical environmental elements that must be changed to support heart health. This reduces the risk of cardiovascular disease and contributes to healthier communities. Researchers, leaders, medical professionals, and community people may all learn more about avoiding heart disease and develop better ways to enhance heart health and general well-being by collaborating across disciplines (Fatima, 2024; Francis et al., 2023; Vajjhala & Eappen, 2024).

The provided dataset includes a wide range of information about people's health that could be linked to heart disease. It includes demographics like age, gender, race, and socioeconomic status, as well as health indicators like cholesterol, blood pressure, and how well their heart responds to stress. The dataset also includes information about their lifestyle, such as how often they exercise, how hard they exercise, and what types of exercise they do. It also includes information about the environment they live in, like the air quality, temperature, and humidity. This dataset can be used by researchers to better understand the causes of heart disease and find the most important risk factors. By employing sophisticated methodologies such as machine learning and deep learning on this dataset, scholars might uncover intricate patterns and connections that may not be readily apparent through conventional statistical procedures. Using the provided data, supervised learning models, for instance, may be trained to identify the primary predictors and risk factors and determine if a person has a history of heart disease. Deep learning models can reveal hidden patterns in the dataset

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and hitherto undiscovered correlations between variables since they automatically learn the hierarchical representations of the data. Additionally, researchers may better understand how well various algorithms perform by visualizing model performance using confusion matrices and accuracy plots. Academics can assess a variety of variables, including accuracy, precision, recall, and others, with the use of confusion matrices. They show the model's prediction accuracy for different classes. By using deep learning and machine learning techniques to this data, we might be able to better understand the risk factors for heart disease and provide individualized prevention regimens(Dey et al., 2024; Rahman et al., 2024; Vajjhala & Eappen, 2024).

AI prediction models are precise and personalized; they may tailor workout recommendations based on particular characteristics, optimizing cardiovascular outcomes. With the use of large datasets and complex algorithms, artificial intelligence (AI) may improve the accuracy of treatments by taking into account variables like genes, socioeconomic position, and environmental impacts. To ensure effectiveness, future research should improve prediction models and assess their performance across different populations. AI algorithms enable physical activity treatments to get real-time input and adjust accordingly. This allows for real-time feedback and adaptation. By constantly analysing data and changing recommendations based on individuals' reactions, AI-driven platforms can increase adherence to and the effectiveness of the intervention. However, to maximize adoption and accessibility, it is important to develop user-friendly interfaces and smoothly integrate AI technology into current healthcare processes to maximize adoption and accessibility. It is critical to protect patient privacy, ensure data security, and prevent prejudice. Transparent communication and strict governance are essential for maintaining trust and encouraging the responsible use of AI in this field. Paraphrased Text, Collaboration for AI Guidelines, Government agencies should work with healthcare professionals to create rules and best practices for developing, using, and testing AI in heart disease care. Multi-Disciplinary Integration, to use AI tools effectively, people in cardiology, data science, psychology, and public health need to work together. Discussions around AI for Human Learning and Behaviour Change through Physical Fitness will remain limited if there is no recognition of how AI provides cues that encourage individuals to be proactive in managing their health. The importance of measuring heart rate, amount of activity, or even the change in VO2 Max in assessing fitness levels provides such information to the AI models which can, therefore, predict heart diseases in patients much earlier creating a feedback loop that modifies behaviour for health promotion. Such modification of behaviour is also facilitated through health-related behaviour modification approaches where the patient is given information directly about their health status and personal conduct and how that modifies their exercise, dietary or general lifestyle patterns. It is also important to note that when fitness gadgets are being worn or their respective software used, it is possible to advise on change of behaviour at any particular time that warrants such a change, which aids in enhancing the desired behaviours and ensuring behaviour change is achieved in the long haul. Incorporating this type of support not only assists the participants in becoming proficient in health education but also develops their interest in healthier practices thus possibly reducing the chances of developing cardiovascular diseases in the years to come.

Combining AI with diverse skill teams can improve collaboration, information sharing, and patient outcomes. Knowledge and Creativity, Schools should provide programmers' where professionals from many professions may learn from one another and possibilities for collaborative research in order to foster innovative thinking and collaboration in the prevention of heart disease. It's critical to employ trustworthy outcome indicators, such as cardiovascular events, quality of life, and healthcare utilization, in order to fully evaluate the effects of AI technology. Economic analyses are also required to determine the worth of AI-driven interventions and direct the distribution of resources. AI has the potential to transform preventive cardiology by boosting cardiovascular health, optimizing medications, and customizing recommendations for physical exercise. But

in order to realize AI's full potential, implementation, ethical, and legal issues must be resolved. Cooperation, openness, and long-term assessment planning are necessary to guarantee that AI-driven therapies successfully improve cardiovascular outcomes. The main points of discussion and recommendation are:

- Need of comprehensive risk assessment for heart health of each individual, environmental, lifestyle, medical and habitual factors.
- Need to highlight the link between regular moderate to high intensity exercise, which can reduce heart disease risk.
- Environmental influences are most important factor, the temperature and air quality on heart health, it can be considered for further research.
- To develop a recommendation system, which can use for testing, promoting exercise programs and it will be helpful for urban peoples to improve heart health.

Mental healthcare

The benefits of physical exercise on mental health have been acknowledged more and more, not only in prevention but also in cure. Physical exercises, especially performed regularly, help to release endorphins and neurotransmitters such as serotonin and dopamine, which are responsible for mood stabilization and lowering anxiety as well as depression levels. In addition, everyday aerobic activities such as walking, running, or riding a bicycle have a positive effect on cognitive abilities as well as on resistance to emotional disturbances. The AI models used in this research pointed out consistent associations between physical exercise and lower levels of psychological distress, indicating that properly designed exercises can be a beneficial strategy to enhance one's state of mind. Such observations justify exercise-oriented schemes in health management and illustrate the importance of physical activity in mental health preservation. Physical activities not only enhance mental health but can be beneficial in treating ailments related to the brain as well. Regular exercises have been proven to increase the process called neuroplasticity that some of the neurodegenerative disorders like Alzheimer's, anxiety, depression, epilepsy, and Parkinsons may not progress quickly. The result of the analysis revealed that those individuals who maintained a regular exercise took appeared to perform better on the cognitive markers and had fewer declines due to age. This way of integrating AI models turns out to help us understand how particular patterns of physical exercises affect the state of the brain with regards to neurological health creating room for such interventions to be tailored to individuals. This kind of management helps to promote even the prevention of diseases through better health education and practice (Dey et al., 2024; Fatima, 2024; Francis et al., 2023; Rahman et al., 2024; Tiwari & Waoo, 2024; Vajjhala & Eappen, 2024).

Future direction

Our findings pave the way for further investigations mental healthcare and prognosis. We may include data from wearable devices or genetic markers into these algorithms to improve their ability to forecast the risk of heart disease. This will enable us to determine the population most vulnerable to heart disease. Second, research into mental healthcare care prevention strategies, such as encouraging physical activity and leading healthier lives, is needed. Long-term research will provide insight into how long-term lifestyle modifications impact cardiovascular health. Using wearables and other digital technologies, physical activity and healthy habit compliance may be tracked in real time. Research insights can be gained from examining the complex interaction between environmental variables and heart health. Analysing the relationship between heart disease risk and environmental factors, such as air quality or climatic variations, can direct policy and urban planning initiatives towards the creation of healthier environments. To put initiatives that lower environmental dangers and build heart-friendly cities into action, academics, policymakers, and city planners must work together.

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Improving heart disease prediction models, creating and executing lifestyle modifications, and investigating the influence of environmental variables on heart health should be the top priorities for future study. We may work to lower the global burden of heart disease and enhance people's general health by expanding our knowledge of the intricate causes of heart disease and putting research results into useful solutions. Furthermore, future research in preventive cardiology may benefit from focusing on enhancing precision medicine by using AI to customize therapies based on unique genetic profiles, biomarkers, and lifestyle variables. Multimodal Data Integration: Merging information from many sources (such as sensors, questionnaires, and medical records) is increasingly crucial for comprehending heart health risks and behaviours. To make this data more helpful for developing individualized treatment plans, researchers must devise new methods for integrating and analysing information using artificial intelligence (AI) tools. Interpretability and explainable AI, it's critical to make sure we can comprehend AI algorithms' inner workings and provide justification for their conclusions as they grow in complexity and are employed in healthcare more often. Researchers must devise techniques that improve the transparency, interpretability, and explainability of AI algorithms.

Future research can leverage AI, such as reinforcement learning and tailored nudges, to create personalized interventions that are effective, engaging, and long-lasting. AI-powered approaches in preventive cardiology can be tailored to individual needs and barriers by using principles from behavioural economics and psychology. To ensure fair access and acceptance of these approaches, bridging the gap between research and practice is crucial. Implementation Science in Future Studies; Future research should use principles from implementation science to find obstacles and factors that help the roll-out of interventions. Interventions should be, culturally sensitive, linguistically appropriate, accessible to marginalized populations, longitudinal monitoring and predictive analytic s, instead of just looking at risk factors at one time, future research should focus on creating AI systems that, continuously track people's heart health over time. Predict future risks based on these patterns. Future research direction can be explored in near future:

- Enhance and validate ML and DL models for better heart disease risk prediction.
- Study long-term effects of lifestyle changes on heart health with real-time monitoring.
- To develop a policy for heart disease risk and environmental factors.
- Exploring personalized AI tools for better healthcare recommendations.

AI-driven insights to further refine personalized exercise recommendations aimed at improving mental health and preventing neurological decline. Longitudinal studies with larger and more diverse populations are needed to validate the impact of specific types, durations, and intensities of physical exercise on mental well-being and cognitive resilience. Additionally, integrating data from wearables and fitness apps with AI models could provide real-time monitoring, enable early detection of mental health issues and offer timely, personalized interventions. This could revolutionize preventative healthcare by promoting both physical and psychological well-being through tailored fitness strategies.

CONCLUSIONS

This research explored the use of machine learning and deep learning models to forecast heart disease history based on various input factors. These models can help stratify risk and detect cardiovascular problems early, allowing for individualized healthcare interventions based on personal risk profiles. The study found a connection between physical activity and heart health; those who regularly engaged in moderate to vigorous exercise had lower heart disease rates. This emphasizes the importance of incorporating exercise into daily routines to reduce cardiovascular risks. Other demographic factors, such as age, gender, ethnicity, and socioeconomic status, were also considered in the study. Lifestyle choices such as diet, smoking habits, and

alcohol consumption also showed associations with cardiovascular risk factors, highlighting the importance of addressing modifiable lifestyle factors in preventing heart disease. Developing research into therapeutic and preventative mental and heart disease therapies need strong cooperation with medical professionals and decision-makers. Together, we can create personalized plans that help individuals live heart-healthy lives by encouraging collaboration and information sharing. Optimizing AI implementation in conjunction with patients' physical activity data offers enormous prospects for enhancing cardiovascular health. Artificial intelligence models can allow making behavioural changes in individuals by turning the fitness numbers into healthy actionable insights and helping them take preventive measures against coronary artery disease. This combination of sophisticated analytics and live interactions holds a great promise in promoting sustainable behaviour change, which will not only benefit the individuals but also the general public health. Engaging in regular physical activity plays an important role in the enhancement of mental health and cognition, which in turn may reduce anxiety, depression, and neurological disorders. Improving these effects by applying AI models to tailor exercise recommendation is a plus, thus encouraging overall wellness.

AUTHOR CONTRIBUTIONS

W. J.: conceptualization, investigation, visualization, resources, supervision, funding acquisition. C. H.: resources, supervision, formal analysis, funding acquisition. R. A.: investigation, formal analysis, supervision, resources, project administration. M. S. I.: writing - original draft, funding acquisition, investigation, validation, supervision, formal analysis. M. B. B. H.: investigation, visualization, formal analysis, supervision, data curation.

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No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

Data will be available at the author's request.

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ORIGINAL ARTICLE

The impact of baskin on promoting inclusion in a secondary school

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ABSTRACT

The impact of Baskin on promoting inclusion in a secondary School is one of the fundamental goals in the education of adolescents with and without disabilities. Baskin, an inclusive sport inspired by basketball, aims to encourage the active participation of all students regardless of their physical and cognitive abilities. This experimental study with a randomised parallel group design investigated the effects of a Baskin programme (12 weeks, two sessions per week) on class cohesion, self-esteem and inclusive attitudes in a secondary school. At the end of the intervention, the experimental group showed a significant improvement in all indicators of social inclusion and psychophysical well-being compared to the control group. The results highlight the potential of Baskin as an educational sport strategy to promote inclusion and the overall development of students.

Keywords: Physical education, Educational sport, Self-esteem, Class cohesion.

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INTRODUCTION

In recent decades, school inclusion has emerged as a guiding principle in national and supranational education policies, in harmony with the UN Convention on the Rights of Persons with Disabilities and Goal 4 of the 2030 Agenda, which aims to 'ensure quality, equitable and inclusive education for all' (UNESCO, 2009; UNESCO, 2020). The underlying assumption is that every student, regardless of physical, cognitive or sensory abilities, should be able to participate fully in school life and benefit from equal learning opportunities (Armstrong, 2003). Within this framework, physical education and sport have a strategic role to play: the cooperative nature of motor activities promotes peer interaction, the development of social-emotional skills and the creation of a positive classroom climate (Avramidis & Norwich, 2002; Sabo & Veliz, 2008). Empirical evidence suggests that team experiences, when well structured, enhance a sense of belonging, empathy and pro-social behaviour (Lindsay et al., 2020). Conceived in Italy in the early 2000s, Baskin is one of the most innovative proposals in the field of inclusive sport: it retains the competitive logic of basketball but introduces flexible rules, baskets at different heights and differentiated roles to make each participant indispensable to collective success (Bortolotti & Tavazzi, 2020). Qualitative studies have reported benefits for group cohesion, self-efficacy and acceptance of diversity (Zoia, 2016; Cummings, 2018). Nevertheless, controlled experimental evidence remains scarce, particularly in secondary school contexts (Kasser & Lytle, 2013; Healy, Msetfi & Gallagher, 2022). In light of this gap, the present paper uses a parallel group randomised design to assess the effects of 12 weeks of Baskin on:

1. Class cohesion;
2. Self-esteem;
3. Inclusive attitudes towards peers with disabilities.

It is hypothesised that the experimental group will show significantly greater improvements than the control group on all the psychosocial indicators considered.

METHODS AND TOOLS

Studio drawing

The study used a randomised parallel group design with pre- and post-intervention measures, similar to what has been proposed in previous research in inclusive sport settings (Kasser & Lytle, 2013). The total duration of the intervention was 12 weeks, with two weekly Baskin sessions of 50-60 minutes each for the experimental group, while the control group followed a normal PE curriculum without Baskin.

Participants

The final sample consisted of 44 secondary school students (aged 14-15 years), of whom 22 were assigned to the experimental group and 22 to the control group. The sample size was determined on the basis of a statistical power analysis (G*Power 3.1.9.6), which suggested a minimum of 36 participants to detect a medium effect size with $p < .05$ and 80% power. A slightly higher initial number (44) was chosen to compensate for potential drop-outs.

Inclusion criteria

1. Age between 14 and 15 years;
2. Absence of medical contraindications to physical activity;
3. Regular attendance at Physical Education classes.

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Exclusion criteria

1. Absences of more than 20% of the lessons;
2. Lack of informed consent from parents/legal guardians;
3. Specific medical situations arising during the study.

All students and their families signed an informed consent form in accordance with the Declaration of Helsinki as amended (World Medical Association, 2013). The study was approved by Department of Medical, Human Movement, and Well-being Sciences—University of Naples "Parthenope" (DiSMMeB Prot. N. 88592/2025).

Randomisation

Simple randomisation was used to assign students to the two groups (Tafuri et al., 2024): participants were numbered and assigned to the experimental or control group by random number extraction using special software. The staff responsible for the statistical analysis were unaware of the allocation of participants.

Baskin' schedule

The experimental group participated in 24 sessions (two per week for 12 weeks; 50 60' each) designed according to the principles of inclusive physical activity (Kasser & Lytle, 2013) and the guidelines of the Italian Baskin Association (Bortolotti & Tavazzi, 2020). Each session consisted of four phases:

Table 1. Baskin didactics programme.

Phase	**Duration Time**	**Key Goals**	**Strategies/methodologies**
Inclusive Warm-up	10'	Motor activation, socialisation	Invitation' games (lap ball, mirror walking), leading in mixed pairs, using soft balls or ramps.
Technical-tactical workshop	25-30'	Adapted learning fundamentals	Rotating stations (<6 students) on passing, shooting and dribbling; vertical peer tutoring; immediate feedback
Game/match situations	10-15'	Transferring skills in a competitive environment	Skills transfer in a competitive environment Mini-match 4 vs 4/5 vs 5 with 0-5 roles and multiple baskets; role rotation every 5'.
Reflective debriefing	5'	Consolidating social-emotional learning	Circle time: each student shares a success and a goal for improvement

Weekly progression:

- Weeks 1-2: Familiarisation with the rules, definition of roles, agreement on visual communication routines.
- Weeks 3-6: Development of basic skills; cooperative micro-challenges to strengthen cohesion.
- Weeks 7-10: extended matches with compulsory role rotation; introduction of team goals.
- Weeks 11-12: internal tournament between mixed teams, with joint formative evaluation by teachers and students.

Inclusion support devices:

- Co teaching (EF teacher + support teacher).
- Structured peer tutoring.
- Individual motor skills portfolio (monitored every fortnight).
- Adapted materials: balls of different sizes/weights, adjustable baskets, numbered bibs indicating roles, colour markers for the shooting areas.

The control group attended two lessons per week of traditional physical education (volleyball, standard basketball, basic athletics).

Evaluation tools

- Class Cohesion Questionnaire (QCC): adaptation of a validated instrument (Di Palma et al., 2023) with 15 items on a Likert scale (1 = strongly disagree; 5 = strongly agree) to measure cooperation, respect and group climate.
- Rosenberg Self-Esteem Scale (RSES): 10 items with scores ranging from 0 to 30, with higher scores indicating higher self-esteem (Rosenberg, 1965). It is a widely used measure in youth research (Boardley, 2013).
- Inclusive Attitude (AI) Scale: 8 items constructed from previous studies on school inclusion (Avramidis & Norwich, 2002; Zoia, 2016) to assess students' propensity to support and accommodate peers with different abilities. Items were rated on a Likert scale (1-5).

The evaluations were carried out before the start of the programme (T0) and after 12 weeks (T1), during school hours, to ensure the anonymity of the participants.

Statistical analysis

The evaluations were carried out before the start of the programme (T0) and after 12 weeks (T1), during school hours, to ensure the anonymity of the participants. Analyses were carried out using IBM SPSS® software (version 25.0). A repeated measures ANOVA (time: T0 vs. T1 × group: experimental vs. control) was performed for each of the variables studied (QCC, RSES, AI). In case of significant interactions, paired t-tests were performed for pre-post comparisons within each group. A significance level of $p < .05$ was used (Cohen, 1988).

RESULTS

Class cohesion

The repeated measures ANOVA revealed a significant group × time interaction ($F(1,42) = 10.34$; $p < .01$; $\eta^2 = 0.42$). Specifically, the experimental group achieved a mean increase of 5.2 points ($p<0.001$) on the QCC scale (mean increased from 45.1 ± 5.0 to 50.3 ± 5.2), whereas the control group experienced a minimal and non-significant increase (+1.0 point; $p > .05$).

Self-esteem

For the Rosenberg scale, the interaction group × time was significant ($F(1,42) = 8.88$; $p < .01$; $\eta^2 = 0.35$). In the experimental group the mean increased from 18.3 ± 2.1 to 22.6 ± 2.4 ($p < .001$), whereas in the control group the increase was smaller (from 18.1 ± 2.0 to 19.0 ± 2.3; $p > .05$). These data confirm the effectiveness of an integrative sports programme in improving self-perception in adolescents (Sabo & Veliz, 2008).

Inclusive attitude

The Inclusive Attitude scores also showed a significant interaction ($F(1,42) = 9.42$; $p < .01$; $\eta^2 = 0.39$). The experimental group increased from a mean of 24.5 ± 3.1 to 27.6 ± 3.3 ($p < .01$), whereas the control group showed a non-significant increase (from 24.3 ± 3.0 to 25.2 ± 3.2; $p > .05$). This suggests that Baskin may contribute to increasing boys' propensity to welcome and support peers with different abilities (Cummings, 2018).

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DISCUSSION

The Inclusive Attitude scores also showed a significant interaction ($F(1,42) = 9.42$; $p < .01$; $\eta^2 = 0.39$). The experimental group increased from a mean of 24.5 ± 3.1 to 27.6 ± 3.3 ($p < .01$), whereas the control group showed a non-significant increase (from 24.3 ± 3.0 to 25.2 ± 3.2; $p > .05$). This suggests that Baskin may contribute to increasing boys' propensity to welcome and support peers with different abilities (Cummings, 2018).The results obtained underline the effectiveness of Baskin in promoting inclusion and well-being in a school context, confirming previous research on the importance of adapted sporting activities in fostering group cohesion, self-esteem and inclusive attitudes (Bortolotti & Tavazzi, 2020; Zoia, 2016). This evidence appears to be in line with more recent studies that highlight how the inclusion of inclusive sports practices, with specially calibrated rules, can facilitate the active participation of students with and without disabilities, improving their perceptions of self-efficacy as well as school motivation (Darcy & Lock, 2020; Mladenov, 2022). The significant increase in class cohesion scores found in the experimental group is consistent with a growing body of literature highlighting how team sports can act as a means of creating a climate of collaboration and mutual support (Avramidis & Norwich, 2002; Lindsay et al., 2020). Basketball in particular is characterised by the need for collaboration between peers with different abilities, making each participant an active and valued part of the group (Cummings, 2018). This promotes the reduction of relational barriers and the construction of a positive collective identity, as noted in a number of studies that highlight the power of the group to support itself in everyday school challenges (Healy, Msetfi & Gallagher, 2022). Furthermore, according to the most recent international guidelines on inclusive education (UNESCO, 2020), interventions that promote collaboration between students with and without disabilities play a crucial role in building a more cohesive classroom climate that respects diversity. Indeed, the game dimension, typical of Baskin, stimulates empathy and solidarity (Darcy, Maxwell & Edwards, 2023).

The improvement in self-esteem, especially in the experimental group, is consistent with the proposition that an inclusive sport context can increase self-perception and confidence in one's abilities (Rosenberg, 1965; Boardley, 2013). Receiving positive feedback from peers and the teacher, playing a meaningful role in the game and experiencing small personal successes are factors that increase satisfaction and motivation (Sabo & Veliz, 2008). Recent studies on adolescents and integrated sport highlight how the collaborative structure and the possibility of adapting the game to each student's abilities lead to improvements not only at the motor level, but also at the emotional and identity level (Freire, Marinho & Monteiro, 2022). Such a dynamic seems particularly relevant in the adolescent phase, where the need for recognition and belonging is high (Graham, 2021). By emphasising everyone's participation, Baskin allows even students with reduced motor or cognitive abilities to feel an active part of a shared project, increasing their self-esteem and self-acceptance. Basketball's ability to reinforce inclusive attitudes lies in its focus on recognising and valuing diversity (Bortolotti & Tavazzi, 2020).

The adaptation of rules and the articulation of playing spaces force students to reframe their notion of 'ability' and focus on the unique competencies of each teammate (Cummings, 2018). This can help to overcome stereotypes and prejudices and encourage the development of positive peer relationships (Mladenov, 2022).In a broader perspective, Baskin fits into an international debate on the use of innovative teaching methodologies aimed at promoting a culture of inclusion (Kasser & Lytle, 2013; Darcy & Lock, 2020). The data from this study showing a significant increase in inclusive attitudes reinforces the idea that well-designed sport interventions can be an effective tool for diversity education (Zhang, 2022). Furthermore, recent literature highlights how inclusive attitudes, when cultivated in the school environment, can have positive effects outside of the educational context, influencing young people's ability to interact empathetically and respectfully in everyday life (Darcy, Maxwell & Edwards, 2023).

Limitations and future prospects

Although the data confirm the beneficial effects of Baskin, the study has some methodological limitations. The 12-week duration does not make it possible to determine whether the benefits observed are sustained in the long term, and the lack of remote follow-up makes it difficult to assess the stability of the behavioural changes. It would be desirable in future research to introduce a more in-depth qualitative evaluation (e.g. through field observations or interviews with students) in order to understand the psychological processes underlying the changes that occurred.

Secondly, the small sample size and single school affiliation limit the generalisability of the findings. Future studies could enlarge the sample, include institutions with different socio-cultural characteristics, or evaluate the effectiveness of Baskin with other age groups. Finally, it would be interesting to compare Baskin with other inclusive sports or with different innovative teaching methods in order to identify similarities and differences and to highlight common success factors (Freire, Marinho & Monteiro, 2022).

CONCLUSIONS

The findings of this study provide robust experimental evidence on the effectiveness of Baskin in promoting inclusion and well-being in upper secondary school. In line with systematic reviews on inclusive sports (Darcy & Lock, 2020; Darcy, Maxwell & Edwards, 2023), the 12-week intervention produced significant improvements in class cohesion, self-esteem, and inclusive attitudes.

From an applied perspective, integrating Baskin into the Physical Education curriculum can:

- Enhance school motivation and active participation of both students with and without disabilities, thanks to differentiated yet equal roles (Cummings, 2018; Healy et al., 2022);
- Promote socio-emotional skills (empathy, collaboration, shared leadership) that are fundamental for active citizenship (Lindsay et al., 2020; Freire et al., 2022);
- Support the goals of equity and quality education set out in the 2030 Agenda, providing a replicable model of adapted sports practice (UNESCO, 2020).

From a scientific standpoint, the data confirm that the cooperative dimension and the interdependent role structure typical of Baskin are effective levers for reducing stereotypes and fostering prosocial attitudes towards disability (Mladenov, 2022; Zhang, 2022). This highlights the need for further longitudinal and multicentric studies to:

- Assess the stability of the effects beyond the three-month period;
- Analyse the psychological mechanisms (self-efficacy, motivational climate) mediating the observed outcomes;
- Compare Baskin with other inclusive disciplines to identify both specific and cross-cutting success factors.

Ultimately, Baskin emerges as an educational sport tool capable of combining playfulness with equity, contributing to the construction of more cohesive and respectful school communities — and, by extension, social communities. The large-scale adoption of similar programmes, supported by adequate teacher training and minor infrastructural adaptations, could represent a concrete step towards a truly inclusive school, in line with UNESCO recommendations (2020) and the most recent evidence on sport and inclusion (Darcy, Maxwell & Edwards, 2023).

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AUTHOR CONTRIBUTIONS

The authors noted that there was equal participation in the elaboration of this document.

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ORIGINAL ARTICLE

Analyzing physical determinants of sprint performance with the ball in semi-professional soccer

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ABSTRACT

Speed, strength, and the player's technical skills are among the essential attributes of soccer performance. This study aims to investigate the extent to which tests on selected physical components can predict performance in speed tests in the presence of a soccer ball. Thirty-four semi-professional soccer players participated in this study. Pearson's product-moment correlation was used to determine the relationship between variables. Linear multivariate regression was used to construct a model from the variables (3 speed and 12 strength variables) to predict the time for 10 m and 30 m sprints with the ball and the time for change of direction speed with the ball. Our selected predictors did not show a significant correlation between the 10 m sprint with the ball and the change of direction speed with the ball. The 30 m sprint with the ball was strongly correlated (r = 0.59) with the 30 m linear sprint without the ball. A regression model with independent variables was statistically significant and identified the 30 m sprint as the only predictor ($F_{1,32} = 17.332$, $p < .001$, Adj $R^2 = 0.331$, SEE = 0.157), which can explain 33.1% of the variability of the data in the 30 m sprint with the ball. Our study supports the claim that the development of running speed with the ball is justified in a soccer environment. Incorporating these exercises into the training process may positively impact match performance.

Keywords: Performance analysis, Technical skills, Team sports, Linear regression.

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INTRODUCTION

Soccer is a complex sport. From a physical performance point of view, one finds that the sport requires aerobic, anaerobic, speed, strength, and agility (Sporiš et al., 2011). These components require approximately 1300 movements during a match (Chaouachi et al., 2012). Therefore, the ability to perform quick movements together with changes of direction in soccer and other sports is one of the most critical skills to acquire to improve performance (Beato et al., 2018). Physical performance is accompanied by different factors, such as the technical component of performance (Brito Souza et al., 2020; Hoff, 2005; Konefał et al., 2019). In recent years, soccer has accelerated considerably, as shown by the progress made in the top leagues regarding speed of work with the ball, sprint distance, and number of sprints (Loturco et al., 2019; Wallace & Norton, 2014). Despite the proliferation of methods now available to assess game activity, it is generally accepted that elite players cover around 9–14 km per game, mainly at low intensities (Bradley et al., 2010; Di Salvo et al., 2009; Wisløff et al., 2004). Assuming that a soccer match is 100% of the distance travelled, the players' movement is around 7–12% at high intensity. When sprinting, it is slightly less, amounting to 1–4% (Bush et al., 2015). Di Salvo et al. (2010) also agree with the distance run at high intensity, around 10%; however, they also state that the distance covered in a sprint ranges from 1 to 12%.

One of the predictors of success in soccer matches is the technical indicator of ball possession (Bradley et al., 2013; Jones et al., 2004; Lago-Peñas & Dellal, 2010). Teams with less ball possession can still be successful, but match progression and related tactics are essential (Link & Hoernig, 2017). Several previous studies have shown that possession of the ball positively affects the team's success in the match. When the team is in possession during the match, it means that they can create more attacking plays, which is closely related to the creation of scoring opportunities and, ultimately, scoring the goal itself. Possession of the ball allows the team to initiate the flow of the match at the appropriate moment and also increases the psychological and physiological strain, which increases the chances of positive match outcome (Wang et al., 2022). Running with the ball is incredibly challenging, as the path taken with the ball changes with each touch. This process involves complex and subtle dynamics of the body's movements when interacting with the ball (Hong et al., 2019). In professional matches, only 1.2 to 2.4% of the total distance is covered in the presence of the ball, with the distance also depending on the playing position of the player (Carling, 2010; Di Salvo et al., 2007; Marzouki et al., 2023). Recently, many researchers have shown that running at any speed alone is not associated with a better result in a soccer match. On the contrary, the distance covered with the ball was related to the team's position in the league, which implies that the respective team must have achieved good results (Brito Souza et al., 2020). The speed of the ball is also of great importance, as this indicator is considered essential when trying to achieve a positive result in the match (Zago et al., 2016).

During a soccer match, the lower limbs have to produce a lot of force for the player to perform specific movements such as acceleration, deceleration, jumping, landing, rotational movements, sudden changes of direction, etc. (Maly et al., 2014). Muscle strength plays a vital role in sports performance and injury prevention. The knee extensors are mainly involved in sprinting, jumping, and kicking the ball. The knee flexors contribute to the flexion of the knee joint to improve athletic performance and stabilize the knee (Lehance et al., 2009). Therefore, predicting isokinetic muscle strength (predicting the state of muscle strength) is essential for performance in a soccer match (Eniseler et al., 2012; Śliwowski et al., 2017). Isokinetic dynamometry is used to predict strength components as one of the most reliable and commonly used methods to assess muscle strength levels (Juneja et al., 2012). A slower muscle contraction is used to engage most motor units. Therefore, isokinetic testing at slower angular velocities of 60°/s is a much better reflection of the composite strength component of the athlete (Fousekis et al., 2010). On the other hand, testing at an angular velocity of 240°/s reflects functional activity (Wilk et al., 2024).

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In a study by Kabacinski et al. (2022), the investigators explored the correlation between the testing of soccer players' muscular strength using an isokinetic dynamometer and their performance in selected tests of speed abilities, including agility. The results of the Pearson correlation demonstrated a statistically significant relationship between the time taken to complete the agility T-test and the strength of the knee joint flexors, measured on an isokinetic dynamometer at an angular velocity of 300°/s (p = .017; r = 0.513) and 60°/s (p = .009; r = 0.557). Sporiš et al. (2011) investigated the relationships between speed, agility, and ball agility tests on a sample of 25 elite young soccer players. The correlation between the zigzag test and the ball zigzag test reached a value of r = 0.479. The specific variables were monitored using an isokinetic dynamometer, and tests were performed to determine the level of speed abilities in a study by Cometti et al. (2001). The aforementioned study also emphasized the maximum velocity of the ball at the point of impact during shooting, which is a significant aspect in the context of a soccer match, along with the respective variables. Makhlouf et al. (2022) demonstrated a relationship between the Illinois change-of-direction test with the ball and the countermovement jump and triple-hop test (r = -0.46 and r = -0.49). The results indicate that vertical and horizontal jump performance can significantly impact COD ability with the ball during the transition phase from deceleration to acceleration in elite soccer players. While the relationships between strength and speed abilities are well established, the strength and speed parameters of running with the ball are somewhat absent in the studies.

The aim of this study is to investigate the extent to which tests on selected physical components can predict performance in speed tests in the presence of a soccer ball. This study assumes that only the minimum time and distance covered during a soccer match are relevant when the ball is present. The ability to accurately detect and potentially predict the given performance (sprint with the ball) could be crucial in achieving a favourable outcome in a soccer match.

MATERIAL AND METHODS

Participants

A total of thirty-four soccer players (age: 21.62 ± 2.19 years, body height: 180.89 ± 6.41 cm, body mass: 76.5 ± 7.49 kg) competing at the semi-professional level (3rd to 5th divisions in the Czech Republic) participated in this study. Given the specific nature of goalkeeper roles, this study deliberately excluded them from the scope of its investigation. Participants must have been active soccer players for at least 10 years. Players completed 3–4 training units of 1.5–2 hours per week and one match per week. All participants were informed about the research and provided written informed consent to participate. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Research Ethics Committee of Masaryk University (EKV-2016-096).

Procedures

The speed test was performed on a wooden surface within the indoor area. A period of 48 hours was observed prior to the commencement of the initial measurement, during which time the participants were prohibited from engaging in high-intensity physical activities. Single-beam photocells (Brower Timing Systems, Draper, Utah, USA) were used for the speed tests, with the resulting test time recorded with an accuracy of 0.01 seconds. The tests completed by the participants comprised a 10-metre sprint, a 30-metre sprint, as illustrated in Figure 1, and a 30-metre double 100° change of direction, as depicted in Figure 2 (Young et al., 2001). When changing direction, the players circumvented a cone measuring 30 cm in height and were instructed to run behind it. If a player touched the cone or dropped it, the test was terminated, and a new attempt was initiated following a two-minute rest period. The initial trials were completed without the ball, followed by subsequent trials with the ball. For the 30-meter tests to be successful, the participant had

to make at least four ball contacts with his feet. In the 10-meter section, the participants were required to make at least two ball contacts. Before the commencement of the actual testing, a standardized warm-up was conducted, followed by two attempts from each test. The participants began each trial in a two-point stance. Each test was completed twice, with a two-minute interval between each attempt. The better time achieved in a given test was always used as the result.

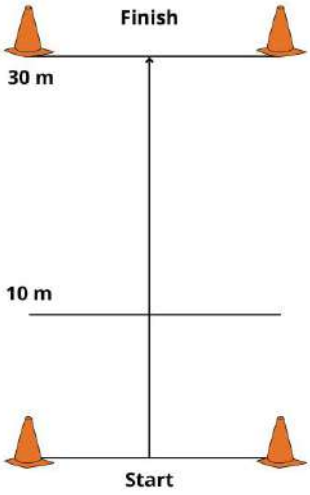

Figure 1. Sprint for 30 m with a split of 10 m.

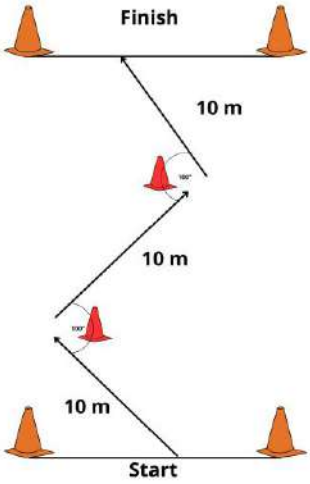

Figure 2. Sprint for 30 m with two changes of direction at an angle of 100°.

The knee flexors and extensor levels were determined using a Humac Norm CSMI dynamometer (Computer Sports Medicine Inc, Stoughton, MA, USA). The testing was conducted in a seated position, utilizing both isometric and isokinetic modes. In the isokinetic mode, an angular velocity of 60°/s and 240°/s was selected, with flexion and extension being measured. An angular velocity of 90°/s was employed in the isometric mode. The right limb was first tested in both modes, followed by the left. Only the trials with the highest achieved power were recorded as measured by angular velocity in degrees per second. Five submaximal repetitions were performed to achieve the maximum power output, with the movement's intensity increasing with each repetition. Each trial commenced with a familiarization phase, after which the subsequent five trials were conducted with a continuous increase in force output. The force exerted during each repetition was incrementally increased by 20% from the preceding attempt until the fifth attempt; at this point, the force reached precisely 100% of the subject's maximal output. A 30-second recovery period was then initiated, after which five repetitions were conducted at the maximum strength intensity. The data employed in the study comprise the maximum values attained in the five performed attempts for concentric flexion and concentric extension. Furthermore, the gravitational constant was also considered.

The following exercises were selected to determine the maximum strength value of the knee flexors and extensors. The lying leg curl workout machine was employed to assess the knee flexors. The seated leg curl workout machine was employed to determine the knee extensors. To ascertain the one-repetition maximum (1RM), the methodology depicted in Figure 3, known as the Baechle protocol, was employed (Baechle et al., 2008). Before the start of the testing, a standardized warm-up was conducted, comprising a warm-up and dynamic stretching. The weight selected was anticipated to enable the completion of five to ten repetitions. Following a one-minute interval, the load was increased, and three to five repetitions were performed, after which a two-minute rest period was initiated. The load was increased once more, and two or three repetitions

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were performed. This procedure was followed by a three-minute rest interval, after which the load was increased again, and a final attempt at the one-repetition maximum level was made. If this attempt succeeded, a three-minute interval was observed, and the load was increased again. At this point, the final value of the one-repetition maximum was approaching. If the attempt at the expected one-repetition maximum was unsuccessful, a three-minute interval was observed, and the load was reduced.

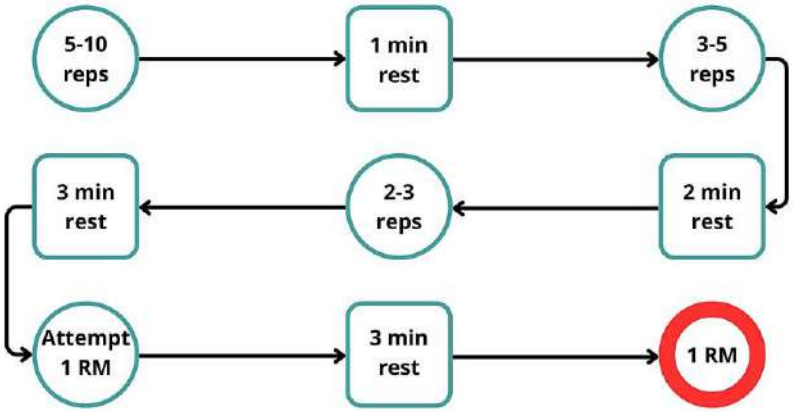

Figure 3. Baechle protocol for 1RM.

Statistical analysis

Data are presented as mean ± standard deviation. The Shapiro-Wilk's test was used to verify the normality of the data distribution, which detected a normal distribution. Pearson's product-moment correlation (r) determined the relationship between variables. The correlation coefficient was interpreted as: trivial (0–0.1), small (0.11–0.3), moderate (0.31–0.5), large (0.51–0.7), very large (0.71–0.9), and almost perfect (0.91–1.0) (Hopkins, 2000).

Linear multivariate regression (enter method) was used to calculate a model from the resulting variables to predict the time in 10 m and 30 m sprints with the ball and the time at the speed of changing direction with the ball. Based on the Pearson correlation, the independent variables with an intercorrelation higher than 0.7 were considered redundant and were removed from the model. Adjusted R squared (Adj R^2) showed us how much percent of the variability of the dependent variable is explained by the independent variables included in the model. The variance inflation factor (VIF) checked the data's multicollinearity. A VIF >10 indicates the presence of more severe multicollinearity (Vincent & Weir, 2012). The level of statistical significance was set at $p \leq .05$. All tests were performed using the statistical software IBM SPSS 28 (IBM Corporation, Armonk, NY, USA) and open-source software JASP (v. 0.19.1) (University of Amsterdam, Amsterdam, Netherlands).

RESULTS

The mean values (± standard deviation) of performances in all speed and power tests are presented in Table 1. The correlation matrix showing Pearson correlation coefficients (r) between all outcome variables is presented in Figure 4. Due to multicollinearity between independent variables (r > 0.7), the following variables were included in the resulting models for tests with the ball: 30 m sprint, change of direction speed, 1RM extension, flexion with the dominant leg in angular velocity of 60°/s, extension with dominant leg in angular velocity of 240°/s, and isometric extension dominant leg.

Table 1. Descriptive statistics of speed and strength performance tests.

Test	Mean	Std. Deviation
Speed tests with the ball		
Sprint_10m_B [s]	2	0.09
Sprint_30m_B [s]	4.73	0.19
CODS_B [s]	7.11	0.38
Speed tests without the ball		
Sprint_10m [s]	1.83	0.06
Sprint_30m [s]	4.33	0.13
CODS [s]	5.92	0.19
Strength tests		
EXT_1RM [kg]	73.5	10.1
FLEX_1RM [kg]	70.79	10.34
EXT_DOM_60 [°/s]	209.56	28.68
EXT_NDOM_60 [°/s]	202.09	30.9
FLEX_DOM_60 [°/s]	119.32	22.23
FLEX_NDOM_60 [°/s]	110.56	21.98
EXT_DOM_240 [°/s]	124.41	16.73
EXT_NDOM_240 [°/s]	123.74	16.78
FLEX_DOM_240 [°/s]	83.06	15.03
FLEX_NDOM_240 [°/s]	77.74	17.17
ISO_EXT_DOM	264.15	39.47
ISO_EXT_NDOM	263.15	45.74

Note. Sprint_10m_B – sprint 10-meters with the ball; Sprint_30m_B – sprint 30-meter with the ball; CODS_B – change of direction speed with the ball; Sprint_10m – sprint 10-meter; Sprint_30m – sprint 30-meter; CODS – change of direction speed; EXT_1RM – knee extension one-maximal repetition; FLEX_1RM – knee flexion one-maximal repetition; EXT_DOM_60 – isometric knee extension with dominant leg, in angular velocities of 60°/s; FLEX_DOM_60 – isometric knee flexion with dominant leg, in angular velocities of 60°/s; EXT_NDOM_60 – isometric knee extension with non-dominant leg, in angular velocities of 60°/s; FLEX_NDOM_60 – isometric knee flexion with non-dominant leg, in angular velocities of 60°/s; EXT_DOM_240 – isometric knee extension with dominant leg, in angular velocities of 240°/s; FLEX_DOM_240 – isometric knee flexion with dominant leg, in angular velocities of 240°/s; EXT_NDOM_240 – isometric knee extension with non-dominant leg, in angular velocities of 240°/s; FLEX_NDOM_240 – isometric knee flexion with non-dominant leg, in angular velocities of 240°/s; ISO_EXT_DOM – isometric knee extension dominant leg; ISO_EXT_NDOM – isometric knee extension non-dominant leg.

All selected predictors show a trivial to moderate relationship (r = -0.03–0.32) with the 10 m sprint with the ball. The regression model for the 10 m sprint with the ball was statistically insignificant with the above independent variables ($F_{6,27}$ = 0.583, p = .741, Adj R^2 = -0.82, SEE = 0.098). All independent variables included in the model were also statistically insignificant and, therefore, could not predict performance in the 10 m sprint with the ball. For the 30 m sprint with the ball, the selected predictors show a trivial to moderate relationship (r = -0.13–0.3), except for the 30 m linear sprint. The 30 m linear sprint was strongly correlated (r = 0.59) to the 30 m sprint with the ball. The regression model with the included independent variables was statistically significant and identified the 30 m sprint as the only predictor. Bivariate regression analysis with one significant independent variable (30 m sprint without the ball) indicates a statistically significant model ($F_{1,32}$ = 17.332, p < .001, Adj R^2 = 0.331, SEE = 0.157), which can explain 33.1% of the variability of the data in the 30 m sprint with the ball. Relationships for the change of direction speed with the ball were at the trivial to small level with predictors (r = 0.06–0.29). The regression model for predicting the change of direction speed with the ball was statistically insignificant, and none of the listed independent variables predict performance in this test ($F_{6,27}$ = 1.002, p = .444, Adj R^2 = 0, SEE = 0.38). Beta coefficients and their 95% confidence intervals, t values, statistical significance of individual predictors, and VIF are presented in Table 2.

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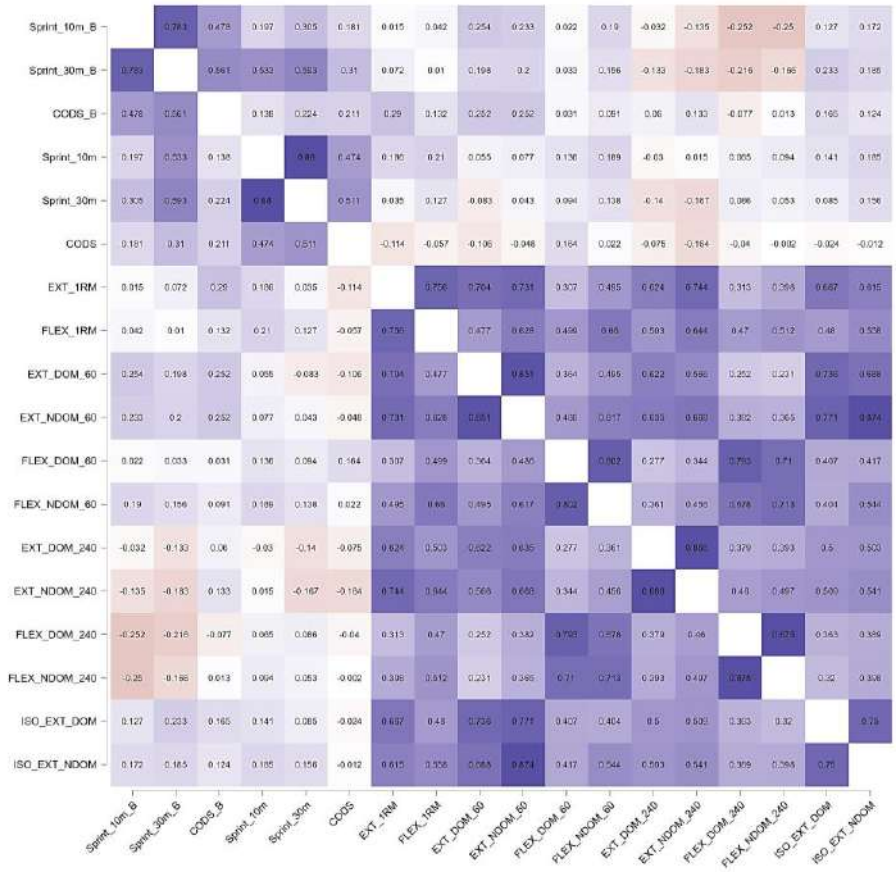

Figure 4. Correlation matrix of outcome variables.

Table 2. Predictors of 10 m sprint with the ball, 30 m sprint with the ball and change of direction speed with the ball.

Test	Unstandardized Coefficients		t	*p*	95% Confidence Interval for B		VIF
	B	Std. Error			Lower Bound	Upper Bound	
Sprint_10m_B							
Sprint_30m	0.191	0.154	1.243	.225	-0.124	0.506	1.467
CODS	0.022	0.106	0.203	.84	-0.197	0.24	1.457
EXT_1RM	-0.001	0.003	-0.351	.729	-0.006	0.004	2.343
FLEX_DOM_60	0	0.001	-0.292	.772	-0.002	0.002	1.26
EXT_DOM_240	0	0.001	-0.058	.955	-0.003	0.003	1.793
ISO_EXT_DOM	0	0.001	0.784	.44	-0.001	0.002	2.007
Sprint_30m_B							
Sprint_30m	0.85	0.204	4.163	<.001	0.434	1.266	1
CODS_B							
Sprint_30m	0.236	0.598	0.394	.697	-0.992	1.463	1.467
CODS	0.443	0.414	1.068	.295	-0.407	1.292	1.457
EXT_1RM	0.017	0.01	1.711	.099	-0.003	0.038	2.343
FLEX_DOM_60	-0.002	0.003	-0.519	.608	-0.009	0.005	1.26
EXT_DOM_240	-0.004	0.005	-0.675	.506	-0.014	0.007	1.793
ISO_EXT_DOM	0	0.002	-0.085	.933	-0.005	0.005	2.007

Note: B – beta coefficient; t: t value; p – statistical significance; VIF – variance inflation factor; Sprint_10m_B – sprint 10-meters with the ball; Sprint_30m – sprint 30-meter; CODS – change of direction speed; EXT_1RM – knee extension one-maximal repetition; FLEX_DOM_60 – isometric knee flexion with dominant leg, in angular velocities of 60°/s; EXT_DOM_240 – isometric knee extension with dominant leg, in angular velocities of 240°/s; ISO_EXT_DOM – isometric knee extension dominant leg; Sprint_30m_B – sprint 30-meter with the ball; CODS_B – change of direction speed with the ball.

DISCUSSION

Our study examined the relationship between selected strength and speed tests and speed tests with the ball. The regression model for the 10 m sprint with the ball was statistically insignificant. Similar results were obtained for the change of direction speed test. The 30-meter test with the ball strongly correlated with the 30-meter sprint without the ball. The regression model with the included independent variables was statistically significant and identified the 30-meter sprint as the only predictor capable of explaining 33.1% of the variability in the 30-meter sprint with the ball data.

We encountered a slight difference in the tests compared to other research. Most studies, such as those by Cronin & Hansen (2005), dealt with the relationships between selected speed and power tests. In a sample of twenty-six males, they demonstrated statistically significant correlations between the achieved performance in countermovement jump height and sprinting at 5 meters (r = -0.6), 10 meters (r = -0.62), and 30 meters (r = -0.56). When comparing our results with other research, where tests in the presence of a soccer ball were also used, we encountered a slight difference. Sporiš et al. (2011) examined the relationships between tests of speed abilities, change of direction speed, and change of direction speed with the ball of elite young soccer players. The correlation between the zigzag and the zigzag test with the ball reached a value of r = 0.479. Makhlouf et al. (2022), in their study on young soccer players, showed a relationship between the Illinois test and the Illinois test with the ball r = 0.65. They also showed a relationship between the Illinois test with the ball and tests for assessing explosive power (CMJ r = -0.46 and triple-hop-test r = -0.49). Based on a 6-week intervention in thirty adolescent male soccer players, Sal-de-Rellán et al. (2024) found that the inclusion of running training with the ball together with resisted sprints training led to improved 5- and 10-meter sprints and improved performance in the zigzag test with the ball. Fiorilli et al. (2017) demonstrated a correlation between the Illinois and Illinois tests with the ball r = 0.917 in 92 young soccer players. Two hundred sixty-seven youth soccer players aged 12 to 19 years were tested in a study by Huijgen et al. (2010), where they demonstrated a correlation relationship r = 0.542 between performance in the shuttle sprint and shuttle dribble tests.

In our case, we did not achieve a positive result of the correlation coefficient between our chosen independent variables and tests on a 10 m sprint with the ball and the change of direction test with the ball. Our sample's technical skill level could cause a negative result in the change of direction test with the ball. Performance in running with changes of direction in the presence of the ball can be considered multifactorial and depends on a combination of physical abilities, such as strength, speed, and the level of technical skills. Optimization of all these components through specific training methods can lead to a significant improvement in performance in changes of direction, which is crucial for success in sports with high demands on agility and speed, such as soccer. The 10 m sprint test with the ball did not show statistically significant correlations. The given results could be because the 10-meter sprint with the ball requires the player not only to accelerate and maintain the achieved speed but also to control the ball precisely during speed. The given possible inhibitory effect causes the physical parameters of our abilities, such as speed and strength, not fully manifest in conditions where movement is controlled and limited by the technique of working with the ball (Simonet et al., 2023). Therefore, although negative, our results support including specific soccer training to improve the technique of running with the ball in training processes. By doing so, we can better prepare players for conditions typical for match situations. It is accurate that linear speed has long been recognized as a fundamental aspect of soccer training. However, our study offers nuanced insights by quantifying how linear sprinting influences soccer-specific ball control task performance. Although these findings may appear confirmatory, they underscore the foundational importance of integrating linear sprint training with technical elements in soccer-specific drills. This perspective aligns with Fiorilli et al. (2017), who emphasized the

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predictive role of linear speed in soccer-specific sprints. By reiterating this relationship in semi-professional athletes, we aim to validate its relevance across competitive levels.

Running with the ball is essential in a soccer match. This activity is used to solve some situations in the match and can potentially help the player create free space and opportunities to score a goal (Barbon Junior et al., 2022). Since the model leaves a significant part of the variability unaccounted for, including more specific soccer exercises that combine sprinting with ball control may increase player performance, which can later be implemented in conditions very similar to a soccer match. The suggestion to incorporate sprint exercises with the ball reflects their importance in soccer-specific contexts, particularly for semi-professional players. While such exercises are standard at youth levels, they are often underutilized in older age groups due to a greater emphasis on tactical and positional training. Our results advocate for maintaining a balance between technical and physical training, especially for players transitioning to higher levels of competition. Furthermore, Sal-de-Rellán et al. (2024) demonstrated that resisted sprint drills combined with ball training significantly improve sprint performance in match-like conditions, reinforcing the value of such practices. Either strength or speed abilities did not considerably predict shorter sprints and sprints with changes of direction. Both of these indicators are very important for soccer performance. Therefore, it would be appropriate to develop the technical component of the player in these types of sprints and sprints with changes of direction. The technical component when working with the ball can play a crucial role. The training process should include short sprints and sprints with changes of direction, where the emphasis would be on acceleration, ball control, and quick change of direction. The combination of speed and technical training could better support performance in short sprints and sprints with changes of direction, and thus, with proper implementation in a soccer match, achieve better results.

One of the limitations of our study could be the number of participants. Although our model reached statistical significance in one of the parameters, the limited number of participants may reduce the statistical power of the analysis. Focus on semi-professional players admittedly limits the generalizability of our findings. The term "*semi-professional*" encompasses a broad range of skill levels, potentially leading to variability in results. Future studies should aim to define this population more precisely and include larger, more diverse samples spanning various competitive levels. Expanding the research scope to younger and elite players would provide a comprehensive understanding of how these relationships evolve across developmental stages. Another possible limiting factor may be that semi-professional players may not demonstrate the same technical and physical skills as professionally trained individuals. These differences are most likely due to the difference in the volume of training units. The study used a cross-sectional design, which limits the possibility of inferring causal relationships between sprint performance without the ball and sprint performance with the ball. Although the model suggests a significant predictive relationship, it is unclear whether improving one necessarily leads to improving the other. A longitudinal study would be more appropriate to determine whether targeted 30 m sprint training without the ball can causally improve sprint performance with the ball.

While isometric strength tests may not directly apply in day-to-day coaching, they offer precise insights into neuromuscular capabilities and can inform individualized training interventions. For example, Spiteri et al. (2013) highlighted the role of isometric strength in change-of-direction performance. Coaches can adapt these findings by incorporating practical strength measures such as single-leg squats or Nordic curls to target muscle groups relevant to soccer performance. Although our study did not directly address this transition, it lays the groundwork for future research linking lab-based assessments with field-relevant training applications. Future research should examine additional variables, reactive agility or sprint biomechanics, to better understand the predictors of sprint performance with the ball. In conclusion, the study confirms the

relationship between general sprinting abilities and soccer-specific sprinting tasks, with the 30 m sprint without the ball being a significant predictor of ball performance. However, a multidimensional approach to training and further investigation of other influencing factors, such as cognitive and technical abilities, are needed to comprehensively understand sprint performance in soccer. To draw generally valid conclusions, we should focus on a larger sample of tested players in the future. In addition, testing different age categories at various performance levels would be optimal to achieve more valid results. We acknowledge that our study did not incorporate variables such as decision-making or situational awareness, which are critical in soccer performance. Agility and speed during match play often involve cognitive demands, such as reacting to opponents and anticipating play dynamics. Incorporating tools like reactive agility tests or video-based decision-making assessments in future research would enrich the understanding of sprint performance in realistic game scenarios. Moreover, position-specific analyses would provide insights into how linear and directional sprints vary by tactical roles, as suggested by recent studies on positional demands in soccer (Ade et al., 2016).

CONCLUSIONS

Our study ascertains a moderate to strong correlation (r = 0.59) between performance in the 30 m sprint without the ball and performance in the 30 m sprint with the ball. This finding suggests that players who exhibit high linear sprint performance without the ball tend to maintain that speed when sprinting with the ball, assuming proficient ball control. Therefore, this statement emphasizes the importance of linear speed as a fundamental factor in soccer performance, even after introducing technical elements such as ball control. Including sprint exercises with ball-specific training in the training process is very beneficial for soccer performance. Since sprinting with the ball is a crucial aspect of soccer, players should regularly train sprinting with the ball in conditions as close to a soccer match. This practice will help to improve the transfer of linear speed to soccer-specific tasks, ensuring that technical skill with the ball is not a limiting factor for sprint speed. It would also be appropriate to include monitoring of strength and speed abilities in training processes, not only from the perspective of developing these abilities but also as a possible prevention of injuries.

Future studies should include larger groups of athletes with different performance levels (e.g., elite, amateur) to determine whether the correlation between sprinting with and without the ball applies to all performance levels. Other predictors, such as cognitive and technical abilities, should also be included. In conclusion, testing strength and speed abilities (with or without the ball) are crucial for more comprehensive soccer performance and potential progression. If we continue to address these areas, future studies may provide deeper insight into how speed and technical abilities influence overall soccer performance, leading to better training approaches and athletic development.

AUTHOR CONTRIBUTIONS

IS – study design, data curation, writing – original draft; TV – study design, data analysis, writing – original draft; JP – conceptualization of the study, writing – review and editing; DB – study design, data curation, writing – review and editing.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS APPROVAL

The study was approved by the Research Ethics Committee of Masaryk University (EKV-2016-096).

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ORIGINAL ARTICLE

The impact of pilates mat training on flexibility and core strength in young female volleyball players

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ABSTRACT

The Pilates method consists of a series of exercises designed to stretch and strengthen muscles, thereby improving muscle elasticity and joint mobility. This study aims to evaluate the influence of Pilates on the spine, lower limbs, and abdominal strength using specific tests. Forty young female volleyball players from University Sports Center of Campobasso were equally randomized into two groups: the Pilates group and the control group. The Pilates group underwent a 32-week biweekly training program (from October 2022 to May 2023) in addition to their regular athletic training. All athletes participated in the following tests: Modified Schober Test (MST) for flexion and trunk rotation, Modified Fingertip-To-Floor Test (MFTFT), Straight Leg Raise (SLR), Popliteal Angle (PA), and Half Sit-Up (HSU). In the Pilates group, the results from the MST for flexion and trunk rotation, SLR, PA, and HSU showed statistically significant improvements 32 weeks after the start of the training protocol ($p < .05$). However, no significant changes were observed in the control group. Additionally, both groups demonstrated significant improvements in MFTFT. These findings suggest that Pilates training can be an effective method to enhance flexibility and performance in young female volleyball players. Coaches should consider incorporating Pilates into their programs.

Keywords: Performance analysis, Flexibility, Pilates method, Trunk rotation, Trunk flexion, Volleyball players.

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INTRODUCTION

Improving sports performance requires a multifaceted approach, combining physical training with psychological interventions to optimize results. The Pilates method, created by Joseph Pilates, exemplifies a body-mind exercise system designed to enhance physical function, pain management, and overall well-being (Di Lorenzo, 2011). Originally termed "*Contrology*," this method emphasizes the connection between mind and body to achieve optimal physical wellness. Key principles of Pilates (breathing, concentration, gravity, precision, control, and fluidity) differentiate it from other fitness modalities (Mętel, 2007), ensuring deliberate, purposeful movements that establish a strong foundation while minimizing the risk of injury (Palermi, 2021).

Central to Pilates is the "*Powerhouse*," or "*Girdle of Centre*," a core region extending from the sternum to the pelvis, encompassing the rectus abdominis, obliques, transversus, latissimus dorsi, lumbar muscles, and gluteals (Muscolino, 2003). Through self-resistance or mechanical resistance from tools like springs, Pilates develops long, strong muscles via dynamic (isotonic, isokinetic, plyometric) and static (isometric) contractions (Fayh, 2018). The effectiveness of the Pilates method is due to the specific repetitive movements that act on neuromuscular plasticity to reprogram the Postural Control System (Takakusaki, 2017 and Ivanenko, 2018), exploiting long-term effects to recreate body symmetry, unlike what happens in asymmetric sports (De Blasiis, 2022). Postural stability, variable not only in dysfunctional subjects but also in healthy ones in relation to different sensory conditions (Fullin, 2022 and De Blasiis, 2023), can be improved by the practice of Pilates. Practicing Pilates yields numerous benefits, including improved muscle strength and tone without excessive bulk, enhanced posture, breathing techniques, reduced waist circumference, fluidity of movement, relief and prevention of back pain, increased self-confidence, and reduced stress (Aladro-Gonzalvo, 2012). Its adaptability to individual goals makes Pilates a versatile exercise method, with routines performed on mats or specialized machines (De Souza Andrade, 2021). For all these reasons, Pilates is particularly suitable for volleyball players who undergo repetitive, intense flexion-extension movements of the lower limbs and spine region during matches. In fact, during the game, they perform transitions from flexed postures during ball reception to extended stances for attacks, jumps, and defensive actions like blocking or spinning demands substantial flexibility, especially for the hamstrings and spine. Some previous studies have analysed the effects of Pilates on volleyball players (Manshouri, 2015 and Ding, 2023) but none focused on the flexibility of the spine and lower limbs using specific tests.

This study investigates the impact of a 32-week biweekly Pilates regimen on volleyball players, focusing on three key areas: (1) spinal range of motion (ROM), critical for posture and spinal health; (2) lower limb flexibility, essential for mobility and injury prevention; and (3) abdominal strength, a cornerstone of balance, stability, and athletic performance. Emphasis is placed on active lumbar flexion, spinal extension, and spinal rotation to evaluate Pilates' holistic benefits. This study hypothesizes that participants will exhibit significant improvements in the targeted variables after the training program.

MATERIAL AND METHODS

Participants

This study was conducted with the collaboration of forty young female volleyball players sourced from the University Sports Center of Campobasso. The participants, aged between 12 and 16 years (mean age: 14 ± 1.48 SD) with a BMI averaging 20.45 ± 2.4 SD, were randomly allocated into two distinct groups: the Pilates group and a control group. To ensure the study's integrity, individuals with a BMI below the 10th per-centile or above the 90th percentile were excluded.

Exclusion criteria

The study's criteria for participation were stringent to maintain a homogenous sample. Exclusions were made for: subjects did not have any pathology/condition that could affect postural setting like fractures, previous traumas, significant scars; no one needed corrective lenses or orthodontic appliances, (Moffa, 2020) and subjects exhibiting heterometry of the lower limbs. Individuals with foot deformities were also excluded from the study. Pathologies, such as flatfoot, can impact plantar support, ambulation, and the standard execution of movements during sports activities. Such conditions can be managed through either conservative treatments or surgical approaches, even in adulthood with open surgery or with a percutaneous surgical approach through a minimal skin incision (Catani, 2021).

Informed consent and ethical considerations

Each participant's parents provided their informed consent to partake in both the study's activities and assessments. The research was granted approval by the local Ethics Committee (approval number: 29/2023). Additionally, all subjects underwent a comprehensive medical-sports examination, confirming their suitability for athletic endeavours.

Study duration and structure

The study spanned a period of 8 months. All participants were actively involved in volleyball, attending three weekly training sessions of two hours each and participating in one volleyball match weekly. Their volleyball experience exceeded a minimum of one year.

Group assignments

Participants were equitably divided, with twenty participants placed in the Pilates mat training group and the remaining twenty in the control group. The Pilates cohort engaged in a specialized 32-week Pilates mat training program, entailing two 60-minute sessions each week. In contrast, the control group persisted with their regular volleyball regimen.

Procedures

For this study, we selected specific tests, given their ease of execution, high reliability, and repeatability, ensuring consistency and accuracy:

1. Modified Schober Test (MST) – Evaluating flexion and trunk rotation.
2. Modified Fingertip-To-Floor Test (MFTFT).
3. Straight Leg Raise (SLR).
4. Popliteal Angle (PA)
5. Half Sit-Up (HSU).

Modified Schober Test (MST) – Evaluating flexion and trunk rotation

The MST test is used to measure the amount of flexion occurring in the lumbar spine. A point is marked midway between the two PSIS, which is the level of S2 then points 5 cm (2") below and 10 cm (4") above that level are marked. The distance between three points is measured, the patient is asked to flex forward, and the distance is measured again. The difference between two measurements is an indication of the amount of flexion occurring in the lumbar spine. Similarly, the subject is asked to bend backward, and the extension range is measured. To measure the rotation ranges two points are marked, one on xiphisternum and other on T12. The distance between these two points is measured. Then the subject is asked to rotate, and the distance is measured again. The difference between two measurements is the amount of rotation occurring in the lumbar spine (Varangaonkar, 2015). MST is a quick and non-invasive way to assess spinal mobility in patients with Ankylosing Spondylitis and other spinal conditions. However, it should be used in

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conjunction with other clinical assessments and diagnostic tests to accurately diagnose and manage these conditions (Ward, 1991 and Tousignant, 2005). The MST eliminates the error in identifying the lumbosacral junction and ensures that the lumbar spine is considered.

Modified Fingertip-To-Floor Test (MFTFT)

MFTFT is a simple clinical assessment tool used to evaluate hamstring flexibility and lower limb function in patients with musculoskeletal conditions. This test is an adaptation of the traditional Fingertip to Floor Test, which is used to assess lower back and hamstring flexibility. The MFTFT is more comprehensive in assessing the flexibility of the lower back, hips, and hamstrings. The FTF test is used to evaluate not only the mobility of the entire spine, but also of the pelvis in the forward flexion movement. In this test the subject is standing on a 30 cm high box. The subject is invited to flex forward with the hands extended downwards and subsequently, having reached maximum flexion, the distance from the fingertips to the top of the box is measured. The results were given in centimetres. The MFTFT is a quick and non-invasive tool that can be used to assess hamstring flexibility and lower limb function in a variety of patient populations (Gauvin, 1990).

Straight Leg Raise (SLR)

The Straight Leg Raise (SLR) test is a commonly used clinical assessment tool for evaluating the presence of lumbar disc herniation and sciatic nerve impingement and lower limbs flexibility. This test involves passively raising the patient's straightened leg while the patient is lying down, to assess the degree of hamstring flexibility and the presence of pain or discomfort in the lower back and/or leg. To perform the SLR test, the patient lies down on their back with their legs straightened. The examiner lifts the patient's leg straight up, keeping the knee extended and the ankle in dorsiflexion, until the patient feels pain or discomfort in the lower back or leg. The angle at which the pain or discomfort occurs is recorded, and the test is repeated on the opposite leg. In patients with normal flexibility and no nerve impingement, the SLR test should result in no pain or discomfort up to an angle of approximately 70 degrees. However, in patients with lumbar disc herniation or sciatic nerve impingement, pain or discomfort may occur at a much lower angle, indicating the presence of nerve compression (Ekedahl, 2012 and Magee, 2013).

Popliteal Angle Test (PA)

The Popliteal Angle Test (PA) is a clinical assessment tool used to evaluate the flexibility of the hamstrings and hip flexors (Duncan, 2004). The test measures the angle between the leg and thigh when the patient's leg is passively extended at the knee joint while lying down. To perform the PAT, the patient lies flat on their back with one leg straight and the other leg bent at the knee. The examiner slowly raises the straight leg until the patient feels discomfort or the heel lifts off the table. The angle between the straightened leg and the table is measured, and the test is repeated on the opposite leg (Gajdosik, 1987). In patients with normal flexibility, the angle between the straightened leg and the table should be greater than 45 degrees. However, in patients with decreased flexibility due to musculoskeletal conditions, the angle may be less than 45 degrees, indicating tightness in the hamstrings and hip flexors. The PAT assesses hamstring and hip flexor flexibility in a variety of patient populations. The knee was extended until the next end point of resistance was felt. To eliminate possible initial muscle stiffness, the extension of the ipsilateral knee was performed 3 times before taking measurements (Ten Berge, 2007).

Half sit-up test (HSU)

The Half Sit-Up Test (HSU) is a clinical assessment tool used to evaluate abdominal muscle strength that can be even used in patients with musculoskeletal conditions such as low back pain or postoperative rehabilitation (Anderson, 2007). The test involves the patient performing a partial sit-up, lifting their head and shoulders off the ground, while the examiner measures the patient's ability to complete the movement and

the degree of abdominal muscle activation. To perform the HSU, the patient lies flat on their back with their knees bent and feet flat on the ground. The examiner holds the patient's feet and instructs the patient to perform a partial sit-up, lifting their head and shoulders off the ground while keeping their arms crossed over their chest (Arab, 2006). The examiner measures the patient's ability to complete the movement, the degree of abdominal muscle activation, and the presence of pain or discomfort. the subject performed as many half sit-ups as possible in 1 min.

Training protocols

Normal training protocol

The control group subjects adhered to their established routine, participating in three athletic training sessions per week.

Experimental (Pilates) training protocol

Participants in the Pilates group attended 1-hour Pilates sessions twice a week, in addition to their regular athletic training.

Pilates protocol description

Mat Pilates is composed of fundamental Pilates movements that primarily incorporate joint motions in sync with specific breathing patterns and an upright posture. The following exercises were included in the regimen: Crisscross, Push up series, Up town, Front back, one leg circle, Swimming prep, Roll-Up, Froggie, Butterfly, Spine Twist, Side Leg Lift, Staggered Legs, Triceps Extension, Heel Squeeze Prone, Prone Hip Extension, Prone Back Extension, Cat Stretch, Side Bend Prep, Spine Stretch, Rolling Like a Ball. The Hundred Movement, that is a classic Pilates mat exercise culminated each session. During the "*Hundred*" movement, participants maintained their feet off the ground in a standard position, bending the knees at a 90° angle. Arms remained elongated, hovering just above the abdominal base, with the head and shoulders elevated off the mat. At the same time, during all Pilates training, subjects were careful to actively use their abs to support their heads during four and six breath repetitions and move their heads up and down energetically (Uzun, 2020). Throughout the study duration, no injuries were reported, and all participants remained committed, with no dropouts.

Analysis

The statistical analysis was performed using IBM's SPSS software (International Business Machines Corporation ("*IBM*"), United States), utilizing paired t-tests to evaluate changes within groups.

Paired t-test was used to compare the pre- and post-training (T0 vs T1) results within the same group. This test assesses if the mean difference between paired observations (before and after the period of the study) is statistically significant, suggesting that the Pilates method significantly impacts the participants.

RESULTS

Modified Schober Test (MST) – Flexion

Modified Schober Test Results showed for the Pilates Group a significant change observed 32-weeks post-training initiation ($p < .001$), while for the Control Group No statistically significant change after 32 weeks ($p = .84$) (Table 1). The Pilates group displayed an average increase of 0.82 cm in flexion, whereas the control group showcased a lesser average improvement of 0.08 cm (Figure 1).

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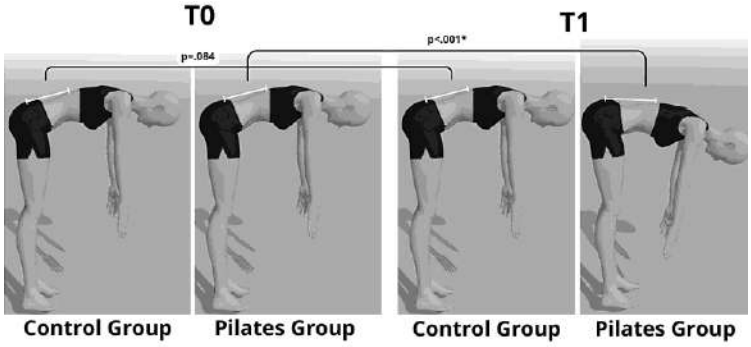
Table 1. This table shows the Modified Schober Test (MST) flexion results (cm).

MST- Flexion	T0 (Mean ± SD)	T1 (Mean ± SD)	T0 vs T1 (*p*-value)
Pilates Group	5.97 ± 0.27	6.79 ± 0.27	<.001*
Control Group	5.96 ± 0.28	6.04 ± 0.36	.084

Note. Significant differences are indicated via asterisk "" (p < .05).*



Note. Significant differences are indicated via asterisk "" (p < .05).*

Figure 1. Visual representation of the improvements observed for Modified Schober Test - Flexion before and after 32 weeks for both control group and Pilates group.

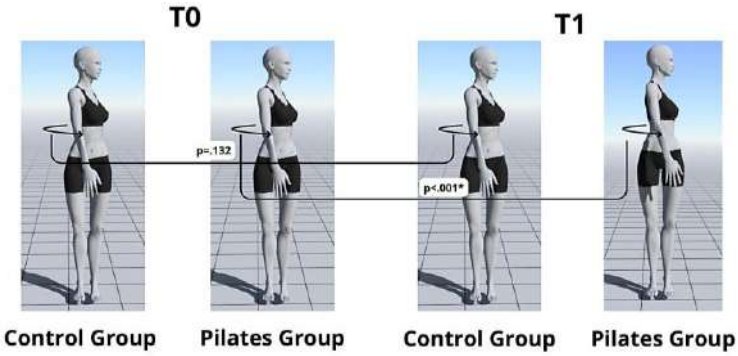
Modified Schober Test (MST) – Rotation

Pilates Group in trunk rotation test had Statistically significant improvement (p < .001). Control Group had No significant change (p = .132) (Table 2). The Pilates group exhibited an average enhancement of 0.23, while the control group's average increment stood at 0.13 (Figure 2).

Table 2. This table shows the Modified Schober Test (MST) trunk rotation results (cm).

MST-Rotation	T0 (Mean ± SD)	T1 (Mean ± SD)	T0 vs T1 (*p*-value)
Pilates Group	2.68 ± 0.22	2.91 ± 0.41	<.001*
Control Group	2.5 ± 0.20	2.63 ± 0.18	.132

Note. Significant differences are indicated via asterisk "" (p < .05).*



Note. Significant differences are indicated via asterisk "" (p < .05).*

Figure 2. Visual representation of the improvements observed for Modified Schober Test - Rotation before and after 32 weeks for both control group and Pilates group.

Modified Fingertip-To-Floor Test (MFTFT)

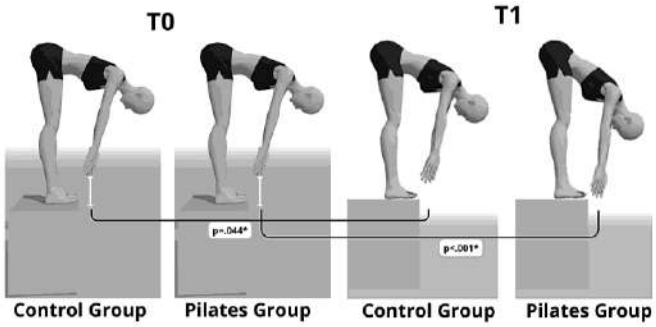
Both the Pilates and Control groups displayed statistically improved results 32 weeks post-training initiation (both p < .05) (Table 3). These results suggest that training both with and without Pilates sessions displayed similar

outcomes concerning the mobility of the spine and pelvis. However, Pilates improves the ROM of the lumbar spine more than conventional training. Conversely, Pilates practitioners observed a prominent average improvement of 3.85 cm, contrasting the control group's average hike of 0.75 cm (Figure 3).

Table 3. This table shows the Modified Fingertip to Floor test (MFTFT) results (cm).

MFTFT	T0 (Mean ± SD)	T1 (Mean ± SD)	T0 vs T1 (*p*-value)
Pilates Group	3.30 ± 1.59	-0.55 ± 1.63	<.001*
Control Group	5.15 ± 1.13	4.40 ± 1.09	.044*

Note. Significant differences are indicated via asterisk "" (p < .05).*



Note. Significant differences are indicated via asterisk "" (p < .05).*

Figure 3. Visual representation of the improvements observed for Modified Fingertip-To-Floor Test before and after 32 weeks for both control group and Pilates group.

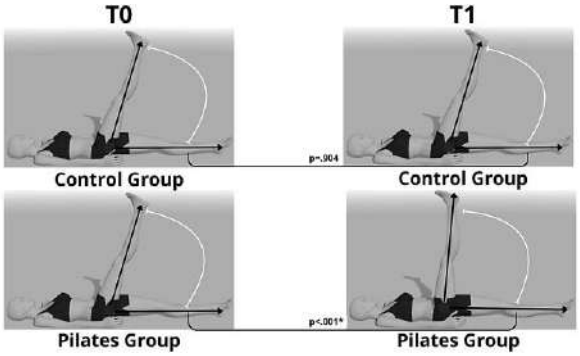
Straight Leg Raise (SLR)

From the results of the Straight Leg Raise (SLR) Test, the Pilates Group exhibited a notable enhancement, as evidenced by a *p*-value of less than .05. On the other hand, the Control Group displayed no significant alteration, with a *p*-value of .904 (Table 4). When examining the average progression, the Pilates participants saw an improvement of 9.7°, which was considerably greater than the modest 0.2° increment observed in the control group (Figure 4).

Table 4. This table shows the Straight Leg Raise (SLR) results (°).

Straight Leg Raise	T0 (Mean ± SD)	T1 (Mean ± SD)	T0 vs T1 (*p*-value)
Pilates Group	65.8 ± 5.8	75.5 ± 4.38	<.001*
Control Group	65.8 ± 5.46	66.0 ± 6.37	.904

Note. Significant differences are indicated via asterisk "" (p < .05).*



Note. Significant differences are indicated via asterisk "" (p < .05).*

Figure 4. Visual representation of the improvements observed for Straight Leg Raise test before and after 32 weeks for both control group and Pilates group.

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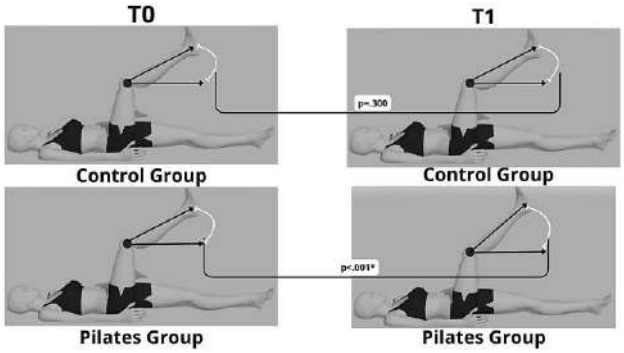
Popliteal Angle Test (PA)

In the results of the Popliteal Angle Test (PA), the Pilates Group showed a significant improvement ($p < .05$). In contrast, the Control Group did not exhibit any noteworthy change, with a p-value of .300. The Pilates group's average improvement was significant at 17.15°, with the control group only registering an average increment of 2.05° (Table 5).

Table 5. This table shows the Popliteal Angle Test (PA) results (°).

Popliteal Angle test	T0 (Mean ± SD)	T1 (Mean ± SD)	T0 vs T1 (*p*-value)
Pilates Group	46.5 ± 5.91	63.65 ± 3.36	<.001*
Control Group	47.05 ± 5.48	49.10 ± 4.95	.3

Note. Significant differences are indicated via asterisk "" ($p < .05$).*



Note. Significant differences are indicated via asterisk "" ($p < .05$).*

Figure 5. Visual representation of the improvements observed for Popliteal Angle Test before and after 32 weeks for both control group and Pilates group.

Half Sit-Up (HSU)

In the half sit-up test results, the Pilates group demonstrated a marked enhancement, with a p-value of less than .05. In contrast, the control group exhibited no such significant improvement ($p = .191$). Specifically, the Pilates group increased their average score by approximately 25.36%. In comparison, the control group saw a more modest improvement, with their scores increasing by 5.10%% (Table 6).

Table 6. This table shows the half sit-up results (as many half sit-ups as possible in 1 min).

Half Sit-Up Test	T0 (Mean ± SD)	T1 (Mean ± SD)	T0 vs T1 (*p*-value)
Pilates Group	31.95 ± 7.1	40.05 ± 5.16	<.001*
Control Group	32.35 ± 7.80	34.00 ± 7.82	.191

Note. Significant differences are indicated via asterisk "" ($p < .05$).*

DISCUSSION

The Pilates method comprises a series of exercises designed to stretch and strengthen muscles, primarily aiming to enhance muscle elasticity and joint mobility. This method is particularly beneficial for volleyball players, who regularly perform repetitive, high-intensity flexion-extension movements of the lower limbs. Players transition from flexed postures during ball reception to extended stances for attacks, jumps, and defensive actions such as blocking or spinning. These movements require a good level of flexibility, especially for the spine and lower limbs. Improved flexibility optimizes performance and reduces injury risk, making Pilates training a valuable addition to volleyball training programs.

This study aimed to evaluate the impact of Pilates on spinal flexibility, lower limb mobility, and abdominal strength using specific assessments. Results from the Modified Schober Test (MST) for spinal flexion and rotation demonstrated significant improvement in the Pilates group after 32 weeks, suggesting enhanced spinal flexibility. The trunk rotation assessment further highlighted the positive effect of Pilates on rotational mobility of the thoracolumbar spine, an essential factor in injury prevention, particularly in sports like volleyball, swimming, and tennis. Notably, while some participants showed Schober test measurements below 5 cm, which typically indicates reduced spinal mobility, this was more likely due to age-related factors rather than any pathological conditions. Thus, the MST results support the effectiveness of Pilates in improving athletic performance and reducing sports-related injuries.

The Modified Fingertip-to-Floor Test (MFTFT) measured the flexibility of the lumbopelvic junction, revealing a statistically significant increase in both groups, with the Pilates group showing slightly greater improvement. This suggests that Pilates training positively influences spinal flexibility.

The Popliteal Angle (PA) and Straight Leg Raise (SLR) Tests assess range of motion (ROM) in the hip and knee joints, focusing on the hamstrings and hip extension, respectively. Both tests showed substantial improvement after 32 weeks of Pilates training, indicating enhanced lower limb mobility. These findings further reinforce Pilates as an effective method for improving flexibility in the lower limbs.

The Half Sit-Up Test (HSU) demonstrated marked improvement in abdominal strength in the Pilates group compared to the control group. Strong abdominal muscles are crucial for trunk stability, posture, and facilitating smooth transitions between postures, all of which are vital for volleyball players' performance.

Overall, this study indicates that Pilates mat training can effectively improve spinal and lower limb flexibility in young female volleyball players. These results are in accordance with (Manshouri, 2015 and Ding, 2023) who state that Pilates significantly enhances flexibility, which is crucial for volleyball players to perform efficiently and reduce injury risks.

Moreover, as Vaquero-Cristóbal (2015) notes, Pilates not only helps reduce the risks of conditions like obesity, diabetes, and cardiovascular disease but also enhances athletic performance. The specific Pilates exercises selected for this study were aimed at improving core strength, stability, and flexibility, key attributes for volleyball athletes. The results highlight the potential benefits of incorporating Pilates into the training regimen of young volleyball players, offering performance enhancements and injury prevention. Furthermore, engaging in Pilates during adolescence may foster long-term physical activity habits, which is critical given that physical inactivity is a leading risk factor for mortality worldwide (Lavie, 2019).

CONCLUSIONS

Our study highlights the significant potential of Pilates mat training in improving flexibility among young female volleyball players. Volleyball, as a dynamic sport, demands a high degree of physical versatility, where flexibility plays a critical role in optimizing performance, enhancing agility, and minimizing injury risks. Beyond its impact on flexibility, Pilates offers a holistic approach by integrating core strength, posture improvement, and breath control. These attributes are particularly valuable for volleyball players, enabling smoother transitions, more effective jumps, and rapid movements essential for both offense and defence. The comprehensive benefits of Pilates suggest its utility as a valuable component in the training regimens of volleyball players. Coaches, trainers, and sports therapists may consider incorporating Pilates to provide athletes with a well-rounded program that combines flexibility, strength, and endurance. Such integration

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could enhance performance while supporting injury prevention and long-term physical health. While our findings are encouraging, they underscore the need for further research to fully understand the broader impact of Pilates in sports training. Future studies could explore the longitudinal effects of Pilates on parameters such as athletic performance, stamina, and injury resilience. Investigating these aspects in greater detail would not only reinforce the initial insights from our research but also offer a more comprehensive understanding of the role Pilates can play in optimizing training strategies for athletes.

AUTHOR CONTRIBUTIONS

Alessandro Cattolico, Carmine Sellitto and Ciro Ivan De Girolamo conceptualized the project and coordinated the research team; these three authors contributed equally to this work and share first authorship. Carmine Sellitto was responsible for data collection and analysis, including statistical analysis. Stefano Moffa ensured the linguistic accuracy of the manuscript and evaluated the reliability of the tests. Katia Corona contributed to data collection and conducted measurements. Ciro Ivan De Girolamo, Luigi Bagella, participated in data collection and analysis. Germano Guerra co-conceptualized the project, led the research group, and managed athlete coordination. Domenico Tafuri and Antonio De Luca reviewed the manuscript for critical content. Angela Lucariello conceptualized the project and served as a project coordinator. All authors read and approved the final version of the manuscript.

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No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

The impact of coaching advice on motor learning skills, with a particular focus on the role of self-competencies in high-performing athletes

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ABSTRACT

In the context of competitive sports training, it is imperative that athletes receive regular training in self-competence to enhance self-regulation and self-control, thereby empowering them to actively influence their own learning process and mitigate stress. The present study (N = 35, mean age: 17.06) suggests a negative correlation between stress load and self-control (r = -.517, $p < .001$). Concurrently, a positive correlation was identified between self-control and willpower (r = .433, $p < .005$), with willpower also exerting an influence on motor learning, although not significantly (d = .358). The study set out to examine the hypothesis that the manner in which coaches communicate has a significant impact on motor learning (r = -.41, $p < .005$). Subsequent group comparisons revealed significant variations in juggling performance, which were associated with higher expressions of willpower ($p = .027$, d = .735). In comparison with the groups that achieved high self-competence scores, the group that received negative coach instruction and simultaneously exhibited a low level of self-competence demonstrated the poorest results in motor learning and exhibited significant differences to the athletes with high self-competence ($p \leq .020$, $d \geq 0.75$). These results underscore the significance of promoting self-competence in top athletes.

Keywords: Performance analysis, Motor learning, Coaching advice, Self-competences, Willpower, Self-regulation.

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INTRODUCTION

A positive sporting career is characterised by both highs and lows. Furthermore, an athlete's convictions and skills are key factors in their ability to cope positively with difficult phases and prevent a premature dropout. These stress-reducing mechanisms, termed coping, can be associated with the problem itself through avoidance tactics or the reduction of competition goals. Alternatively, action strategies can be adopted to regulate emotions, thereby rendering high sporting goals as positive challenges rather than sources of stress (cf. Semmer, 2009). Positive emotions and a positive approach from coaches appear to be beneficial in the context of achieving sporting goals, thereby engendering optimism towards a sporting task (cf. Semmer, 2009). Positive coaching is of particular importance for young athletes, whereby empathy, triggered by positive coaching instructions, plays a decisive role (Visek et al., 2015; Wekesser et al., 2021; Jowett, Yang & Lorimer, 2012). In their meta-analysis with over 11,000 participants, Solberg Nes and Segerstrom (2006) posit that optimism exhibits a weak positive correlation with approaching stress management (r = .17) and a negative correlation with avoiding stress management (r = 0.21). Similar effects with a positive influence on stress management have been demonstrated by Prati and Pietrantoni (2009) and Lowe et al. (2013). Given the strong correlation between optimism and self-efficacy (r = 0.48, Gottschling et al., 2016), it is logical to also consider the expectation of self-efficacy (Bandura, 1977). The dimensions of social and verbal persuasion within the 4-factor model are particularly pertinent to the recent study, in which the coaches' speech and its consequences on motor learning processes are investigated, while focusing on general self-competences such as self-control, willpower, self-regulation and stress load. The aim is therefore to maintain elevated expectations of self-efficacy in challenging situations, with the objective of reducing stress and enhancing problem-coping abilities. The correlation between cognitive abilities and motor learning has been delineated by D'Anna, Mucci and Vastola (2021), among other scholars, and has been corroborated by numerous other authors, with perceived self-efficacy being attributed significant importance (e. g. Gomes et al., 2012).

Increased self-efficacy has been demonstrated to contribute to the setting of more challenging sporting goals, the pursuit of these goals with purpose, and an increase in the overall endeavour to be active in sport (Feltz et al., 2008; Hu, Motl, McAuley & Konopack, 2007). As self-efficacy is defined as a belief in one's own abilities, the survey of self-competences that forms the basis of the present study is of crucial importance (cf. Van Dinther, Dochy & Segers, 2011). This enables the determination of detailed correlations between areas of competence, motor learning and the trainer's approach. The present study assumes that strengthening self-efficacy improves motor learning and that this, in turn, depends on the trainer's approach.

Social factors have been shown to have a supportive effect (Morgenroth & Buchwald, 2015). Zier, Heiss & Ehrlenspiel (2016) have indicated that a high level of intrinsic motivation has a preventive effect against high levels of stress. Furthermore, the authors emphasise that athletes with effective coping mechanisms are better equipped to manage novel demands and consequently exhibit reduced susceptibility to overload (Raedeke & Smith, 2004).

In addition to personality traits, the environment plays a significant role, with coaches in particular exerting a substantial influence due to their role as accepted role models and the significant amount of time and emotional investment they make. When personality traits and environmental characteristics are conducive, stress is reduced, thereby enhancing athletic performance. As demonstrated by Davis et al. (2018), there was an increased cognitive performance (β = -.228, p = .033) when the coach-athlete relationship was perceived as positive. Although this correlation could not be proven for motor learning (β = .019, p = .861), these results indicate possible correlations between learning performance and the coach-athlete relationship.

Heiss et al. (2010) identified motivational, volitional and emotional thoughts that set goals, block negative thoughts and separate thoughts from feelings. The authors refer to the concept of self-leadership, which is defined as the ability to influence self-control and self-motivation processes in such a manner that they are conducive to the challenges encountered (Neck & Houghton, 2006; Heiss et al., 2010). It is further noted that the process of self-leading strategies is predominantly influenced by behaviour-focused strategies, constructive thought pattern strategies, and natural reward strategies (Houghton & Neck, 2002; Heiss et al., 2010).

Baumeister (2014) reports that self-regulatory fatigue (depletion) hinders the mastery of complex sports tasks, a phenomenon termed the 'ego depletion model'. This model establishes a connection between willpower and self-regulation, both of which serve to increase self-control. Ego depletion is described by some authors as the result of reduced self-control due to reduced resources. In this case, it was preceded by good self-control, which can be regarded as the basis of athletic performance (e.g., Baumeister, Vohs, & Tice, 2007). Despite the lack of substantiation in numerous instances of the ego-depletion model (Jia et al., 2016), the maintenance of adept self-control skills is imperative for the attainment of long-term sporting objectives. The endurance of athletes throughout their careers is facilitated by the ability to surmount both psychological and physiological challenges. Furley et al. (2013) identified differences in basketball sports groups (N = 40) that related to ego-depleted athletes having lower self-control resources and therefore also achieving poorer results in a speeded tactical decision-making task (p = .026, d = .0732).

The hypothesis that willpower is a finite resource, as posited by Baumeister (1998), suggests that its depletion occurs over time in response to frequent and intensive utilisation. However, contradictory evidence suggests that individuals who possess an infinite reserve of willpower exhibit reduced signs of fatigue in comparison to those who believe their willpower is limited (cf. Job, Dweck & Walton, 2010; Evans, Boggero & Segerstrom, 2016; Konze, Rivkin & Schmidt, 2017). Consequently, it can be deduced that cultivating athletes' willpower may be a pivotal factor in preventing attrition. Assuming that heightened willpower corresponds to enhanced self-regulation, a correlation between these two factors can be anticipated in the present study. Concurrently, the hypothesis is that self-control will demonstrate a dependency on willpower and self-regulation, and that a negative correlation with the stress level will be observed, given that increased stress will lead to increased willpower and self-regulation. This will result in an increased need for willpower in order to master sporting tasks despite perceived stress.

From the problems and correlations presented, questions can be derived that relate to the consequences of a positive or negative trainer response for motor learning performance. Using juggling as an example, taking into account co-factors such as existing self-competences, skin conductivity and blood volume pulse, which influence the motor learning process (cf. McEwen, 2013; Gerber & Fuchs, 2018), allows us to formulate hypotheses regarding the relationship between these factors and the motor learning performance in question.

MATERIALS AND METHODS

Study design and participants

The present study comprised 35 participants engaged in competitive sports (11 female, mean age = 17.18, SD = 1.32; 24 male, mean age = 16.96, SD = 1.04). It was hypothesised that none of the participants had prior experience in juggling, thus eliminating the need for a specific entry level. Furthermore, the random assignment of the two groups (positive and negative trainer instructions) was examined for comparability based on the initial self-competence levels of the participants (see Table 1). The distribution of results was visualised through a boxplot, which utilised the Mann-Whitney U-test to analyse the data (see Figure 1).

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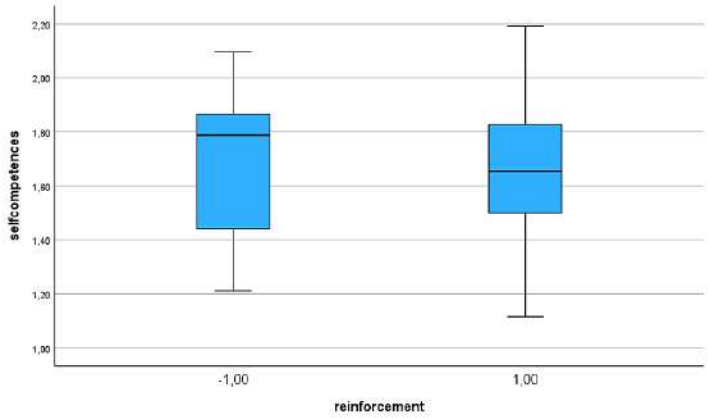

Figure 1. Box plot for the self-competences of the two groups, which were negative (-1) or positive (+1) reinforced by the coaches.

Table 1. Comparison of the groups with regard to their self-competencies, which were randomly given positive or negative reinforcement by the coach (Mann-Whitney U-test).

Motive	Group	N	Mean	SD	Mean rank	*p* (two-sided test)	Asymp. *p* (two-sided test)
Self competences	Neg. reinforced	14	1.67	.42	16.82	.653	.648
	Pos. reinforced	17	1.65	.53	15.32		
Self-regulation	Neg. reinforced	14	1.48	.45	15.75	.891	.889
	Pos. reinforced	17	1.58	.77	16.21		
Self-control	Neg. reinforced	14	1.50	.47	15.25	.681	.676
	Pos. reinforced	17	1.64	.76	16.62		
Will power	Neg. reinforced	14	1.58	.56	15.86	.953	.937
	Pos. reinforced	17	1.66	.52	16.12		
Self-access	Neg. reinforced	14	2.14	.68	17.64	.377	.366
	Pos. reinforced	17	2.06	.60	14.65		
Stress load Life stress	Neg. reinforced	13	1.14	.71	16.46	.621	.599
	Pos. reinforced	17	.97	.67	14.76		

Table 2. Items and Variables of the SSi-K3 including examples for items of each category.

Categories	Items	Examples
Self-regulation	2; 3; 15; 16; 28; 29; 41; 42	In a difficult job, I can look specifically at the positive sides. (15)
Self-control	4; 5; 17; 18; 30; 31; 43; 44	Before I start any extensive work I decide how I am going to proceed. (30)
Willpower	7;8;20;21;33;34;45;46	When something needs to be done, I like to start prefer to start immediately. (45)
Self-access	9;10;11;22;23;24;35;36;37;48;49;50	It's hard to get rid of worrying thoughts once they are there. (48)
Stress-load	12;13;25;26;38;39;51;52	My current living conditions are quite hard. (25)

Measures

The groups were surveyed using the SSI-K3 (German, 2004) with regard to their level of self-regulation (Cronbach's α from .75 - .90). This questionnaire compares 52 items, which were divided into 4 scales each rated on a 6-point Likert scale ranging from 5 = strongly agree to 0 = strongly disagree. The four scales are

divided into the following: self-regulation, willpower, self-access and stress load. The fifth scale (self-regulation) was additionally created because of its importance in educational environments. In addition, skin conductance and blood volume pulse were measured using biofeedback to determine dependencies on possible physical reactions that could have an influence on motor learning performance (Biograph InfinitiTM software, ProComp Infiniti system). The assessment of motor performance was conducted using the 6 learning steps, which were subsequently categorised into learning performance levels 1-6 (see Figure 2).

The descriptive results of the scales are shown in Table 3. The correlations were calculated for all variables and illustrated in Table 4.

Table 3. Descriptive statistics, standard deviations, alpha reliability for main variables in the study and Test for normally distribution.

Variable	**N**	**Mean**	**SD**	**∞**	**Groups of re-enforcement**	**Shapiro-Wilk**	**K - S *p*-value**
Self-competences (total)	35	1.64	.28	.85	Positive	.748	.200*
					Negative	.439	.093
Self-regulation	34	1.60	.37	.75	Positive	.297	.115
					Negative	.400	.200*
Self-control	34	1.57	.47	.68	Positive	.184	.181
					Negative	.364	.200*
Willpower	34	1.58	.49	.82	Positive	.235	.181
					Negative	.683	.200*
Self-access	35	2.04	.61	.90	Positive	.258	.200*
					Negative	.122	.200*
Stress load Life stress	34	1.08	.70	.87	Positive	.068	.134
					Negative	.326	.200*

Table 4. Alpha reliability and correlations for main variables in the study.

Skala	**∞[1]**	**∞[2]**		**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	Self-regulation	>.76	.75	1						
2	Self-control	>.73	.68	.713**	1					
3	Will power	>.79	.82	-.020	.433*	1				
4	Self-access	>.78	.90	.469*	.116	.599**	1			
5	Stress load	>.82	.87	.063	-.517**	-.430*	-.308	1		
6	Motor learning	-	-	-.118	-.019	.358	-.083	-.249	1	
7	Reinforcement	-	-	.028	.112	-.125	-.109	-.125	.41*	1

*Note. **. Correlation is significant at the .01 level (2-tailed), *. Correlation is significant at the .05 level (2-tailed), [1] ∞ - Autor, [2] ∞ - own results.*

Procedures

The participants were randomly divided into two groups. The first group watched a 6-step juggling instruction video while actively following the methodical steps with standardised balls (mass = 100 g) (see Figure 2). The second group watched the same video but received six positively reinforced instructions. The other group received six negatively reinforced instructions. The respective learning step was presented for 30 seconds and simultaneously imitated by the participant. The successful completion of each learning step was assigned a performance score ranging from 1 to 6, with 1 representing the highest level of proficiency. In the event of a cancellation of the motor learning process within a specific learning step, a score of 0.5 was allocated, ensuring a comprehensive and varied dataset.

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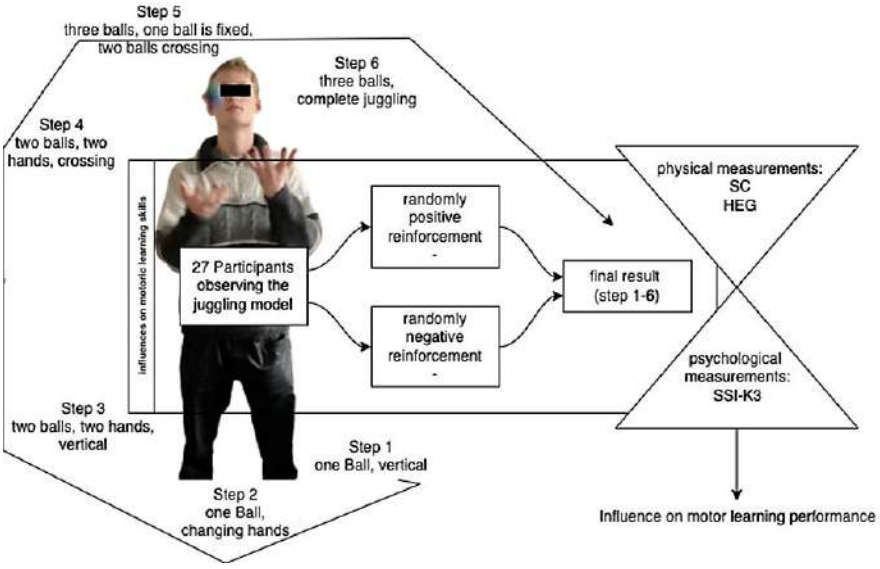

Figure 2. Standardised sequence of the 6-step video instruction for learning to juggle with three balls.

Ethics

The present study was preceded by an authorisation procedure by the local administrative authority (Berlin Senate Administration). Each participant signed a document outlining all data protection issues, as well as the procedure for conducting the study. All instruments that had to be completed by the participants were numbered using a code and will be destroyed within two years. The coding was based on the initials of the mother and her date of birth, generating a ten-digit code. The data collection pertaining to the individual practice performance (juggling) was also coded and followed the same pattern so that the values could be assigned later.

Analysis

The factors of the German SSI-K3 (Kuhl & Fuhrmann, 2004) generally demonstrated good internal consistency, a finding corroborated by other authors (see Table 4). However, a small number of items did not align with the study's requirements and were consequently excluded (see Table 2). Descriptive statistics were calculated for the variables, and the Kolmogorov-Smirnov test was employed to assess the normality of the data. In instances where the data exhibited a normal distribution, the t-test was employed to ascertain the significance between groups. Conversely, if the data did not follow a normal distribution, the non-parametric Mann-Whitney U-test was implemented to identify differences between groups. The subsequent result section involved a comparison between the group with lower self-competences and the group with higher self-competences, with the objective of determining any discrepancies. The groups were arranged in accordance with the mean of each variable.

The effect size was calculated with Cohen's d and interpreted as follows: d = .20 small effect; d = .50 medium effect; d = .80 strong effect (Cohen, 1988). The significance level was set at $p < .05$, and the statistical data treatment was carried out with SPSS 29.0. Pearson's correlation was used for the main variables of the study to analyse the relationship between all the variables. The results demonstrate the effect size (Cohen's d), which was validated by the Hedges correction due to the limited sample size (see Tables 4 and 5). The ANCOVA indicates the potential for variation in the motor learning process between the two groups, influenced by positive or negative reinforcement from the coach's instructions, depending on the impact of any variable (see Table 7).

RESULTS

As illustrated by the diagrams in Figure 3, enhanced self-competence appears to circumvent negative coaching instructions, thereby facilitating the attainment of favourable outcomes. Conversely, diminished self-competence has been observed to result in suboptimal outcomes when confronted with negative coaching instructions. The findings of both presentations substantiate, that positive coaching instructions are conducive to superior learning outcomes, particularly among athletes exhibiting inadequate self-competence. The ensuing discussion will delve into the analysis of these hypotheses. Conversely, the influence of coaches' instructions on willpower is particularly pronounced when willpower is limited and the coaches' approach is negative.

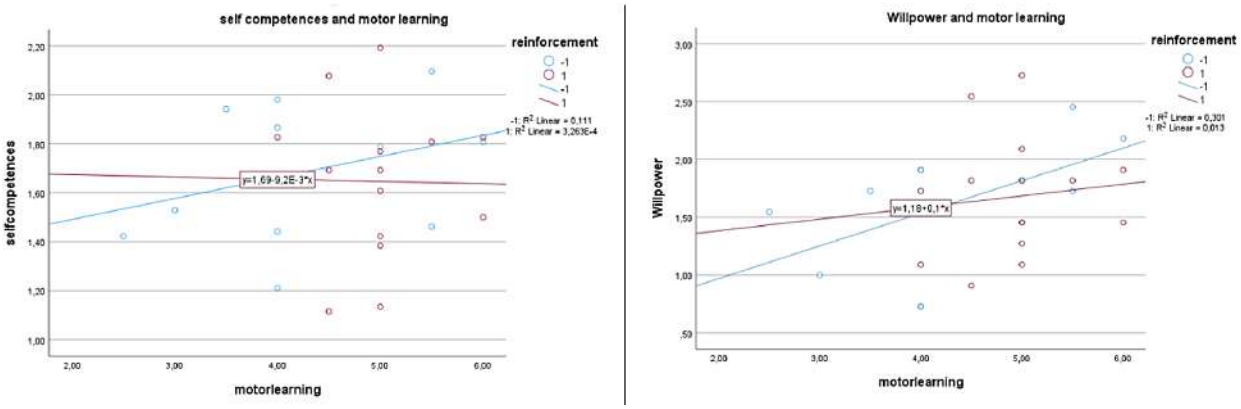

Figure 3. Motor learning success depending on the trainer's approach and the existing self-competences and willpower expression.

In order to analyse the presumed correlations shown in Fig. 3 in detail, the extent to which self-competences influence the motor learning process will be demonstrated in the following section. A one-sided significance test was conducted, as illustrated in Table 5, which revealed that there were differences between the two groups.

Table 5. Differences in motor-learning of the two groups having high or low self-competences-levels (Kolmogorov-Smirnov-*p*-value > .5).

Group		n	Mean	SD	df	T	p	d	K - S *p*-value	Hedges Corr.
Self-competencies	High	16	4.84	.72	28	-.853	.200	-.31	> .05	-.304
	low	14	4.57	1.02						
Self-regulation	High	15	4.87	.83	28	-.945	.176	-.35	> .05	-.336
	low	15	4.57	.90						
Self-control	High	15	4.70	.79	28	.103	.459	.038	> .05	.037
	low	15	4.73	.96						
Willpower	High	14	5.00	.61	28	-2.01	.027*	.735	> .05	.715
	low	16	4.39	1.02						
Self-access	High	14	4.79	.89	28	.402	.345	.147	> .05	.143
	low	16	4.66	.87						
Stress load	High	14	4.57	.89	27	.897	.189	.333	> .05	.324
	low	15	4.87	.88						

*Note. * p = < .05 one-tailed, d = Cohen`s d.*

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Table 6. Alpha reliability and correlations for the relevant sub-categories of willpower in the study.

	Skala	∞	1	2	3	4	5	6	7	8
1	Self-access	.90	1							
2	concentration	.90	.702**	1						
3	Intents	.80	.565*	.662*	1					
4	Initiative	.79	.165	.368	.396*	1				
5	Stressload	.87	-.308	-.361	-.366	-.313	1			
6	Motor-learning	-	.083	.322	.329	.208	-.249	1		
7	SC	-	.023	.260	.263	.108	-.275	.093	1	
8	BVP	-	.087	.147	.187	.153	-.156	.034	.213	1

Due to the limited sample size, the results require alternative recording methods, with the effect size indicated at low significance and subsequently compared with a co-analysis of variance (ANCOVA). The assumption is made that the dependent variable, motor learning, can be predicted by the independent variables (covariates) of self-competences, self-regulation, self-control, willpower, self-access and stress load, with reinforcement taken into account.

The findings reveal that there is no significant difference between the groups with positive trainer instruction and those without effect size (see Table 5). However, the groups with negative reinforcement demonstrate a substantial effect, while the impact is not considered to be significant. It is hypothesised that the factors influencing learning performance are confounding variables. To address this, an ANCOVA is employed for the variables self-competences, self-regulation, self-control, willpower, self-access and stress load.

The hypothesis that the self-competences of the athletes are related to learning performance was examined, and the results are presented in Table 7.

Table 7. Test of between subject effects: ANCOVA, dependent variable: motor learning result of the two groups (positive or negative reinforced).

Variable	Source	Sum Squares	df	F	*p*	Partial η^2
Self-competences	Reinforcement	3.38	1	4.97	.034*	.156
	Error		30			
Self-regulation	Reinforcement	3.16	1	4.59	.041*	.145
	Error		30			
Self-control	Reinforcement	3.221	1	4.67	.040*	.148
	Error		30			
Willpower	Reinforcement	3.02	1	4.90	.035*	.154
	Error		30			
Self-access	Reinforcement	3.24	1	4.70	.039*	.148
	Error		30			
Stress-load	Reinforcement	2.80	1	4.07	.054	.135
	Error		30			

*Note. * p = < .05 two-tailed.*

The Bonferroni-corrected post-hoc analysis revealed a significant difference between the motor learning outcomes of the two positively and negatively reinforced groups ($p < .035$, MDiff = .64, 95%-CI [.047, 1.24]), after adjustment for willpower. After adjustment for self-competence, the results were $p < .034$, MDiff = .68, 95%-CI [.055, 1.31]), after adjustment for self-regulation $p < .041$, MDiff = .66, 95%-CI [.027, 1.28]), and after adjustment for self-control $p < .040$, MDiff = .67, 95%-CI [.034, 1.29]), self-access: $p < .039$, MDiff = .68, 95%-CI [.036, 1.31]) and stress-load: $p < .054$, MDiff = .63, 95%-CI [.012, 1.28]).

No correlations were found for the variables BVP and skin impedance (partial $\eta^2 < .046$, $p > .41$).

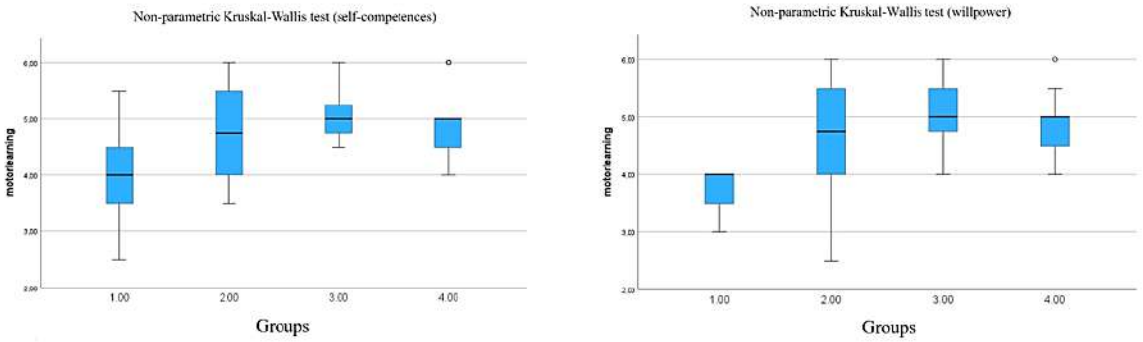

Figure 4. Kruskal-Wallis-test for the variables willpower (right) and self-competence (left) of the following groups: 1: negative reinforcement with less self-competence, 2. negative reinforcement with higher self-competence, 3: positive reinforcement with less self-competence, 4: positive reinforcement with high self-competence.

Table 8. Mann-Whitney-U-Test for the results of motor learning of the four groups and their Willpower and positive or negative reinforcement.

Group	n	Mean	SD	Groups	df	Mean rank	Z	U	*p*
1	3	3.67	.58	1-2	11	4.33 7.80	-1.375	7.00	.169
				1-3	9	2.33 7.38	-2.33	1.00	.020*
2	10	4.55	1.07	1-4	10	2.33 7.89	-2.37	1.00	.018*
				2-3	16	8.45 10.81	-.966	29.500	.339
3	8	5.06	.68	2-4	17	9.15 10.94	-.709	36.500	.49
4	9	4.94	.58	3-4	15	9.44 8.16	-.358	32.500	.720

A Mann-Whitney U-test was employed to ascertain whether there were any discrepancies in motor learning performance between the four distinct groups. The comparisons of groups one and three, as well as one and four, exhibited a statistically significant difference (Kolmogorov-Smirnov $p < .05$). A significant disparity was identified between the motor learning performance of the positively and negatively reinforced trainer instructions, as evidenced by the Mann-Whitney U-test results (U = 1.00, Z = -2.33, $p = .020$; U = 1.00, Z = -2.37, $p = .018$; see Table 8).

DISCUSSION

The present study is to be regarded as a pilot project, to be followed by a significantly larger sample, especially for Group 1, which was ultimately reduced to three participants. This will ensure that generalised statements can be made about the dependencies of learning performance on the sports performance self-competencies of the athletes and on the instructions of the coaches. It is hypothesised that this will lead to optimised implications for the athletes' accompaniment during the difficult steps of a successful dual career

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of sport in school. The enhancement of self-competencies, fostered by constructive coaches' instructions, is poised to yield enhanced performance outcomes, particularly in the domain of motor learning, while concurrently mitigating the occurrence of premature attrition.

Beckmann and Kellmann (2004) posit that self-regulation is of significance in this regard, as it facilitates the identification of the discrepancy between fatigue caused by tiredness and stress and the desirable state of physical and mental activation. This, in turn, can enable the implementation of appropriate measures to achieve the desired state. The knowledge of available resources can also be used to minimise this discrepancy in general, as precautionary measures can be taken, for example, to shorten the time it takes to restore performance (Ziljstra et al., 2014). It can therefore be concluded that self-regulation plays a crucial role in the context of recovery processes. Given the high levels of stress present in competitive sports, the ability to self-regulate is of paramount importance (Kenttä & Hassmen, 1998). The present study's findings, which demonstrate no correlation between self-regulation and motor learning as a function of the trainer's approach, can be explained by the theoretical construct of self-regulation processes (Ziljstra et al., 2014). This is due to the fact that fatigue processes were not to be expected.

In the context of competitive sports training, athletes frequently experience exhaustion, which can result in the development of fatigue syndrome and an increased likelihood of dropout. Self-regulated learning has been demonstrated to be associated with enhanced sporting performance, with self-regulated learners exhibiting elevated levels of personal skills in novel and intricate learning scenarios (Winne & Perry, 2000; McCardle et al., 2019; Wilson et al., 2021; Young et al., 2023). The relationship between self-directed learning processes and awareness of one's own abilities leads to self-efficacy, which is defined as the belief in one's own ability to organise and carry out the courses of action necessary to achieve certain goals (Bandura, 1977, 1995, 2012). Sitzmann and Yeo (2013) investigated the relationship between athletic performance and self-efficacy in the field of sport. Pattinson (2017) investigated the relationship between top divers and their self-efficacy (SE) in relation to performance level. The findings indicated that the more accomplished diving young athletes (aged 9-13 years) exhibited stronger social beliefs ($F (1.175) = 30.69$, $p < .001$) and physiological/emotional states ($F (1.175) = 12.41$, $p = .001$).

According to Bandura's (1977) self-efficacy theory, social persuasion and physiological and emotional states can be considered as sources of this theory. This theory was extended by Feltz, Short and Sullivan (2008), who added physiological and emotional states to the original list of sources, which included mastery experience, vicarious experience, social persuasion, and physiological and affective states. The role of self-efficacy beliefs in maintaining motivation is highlighted, as they facilitate decision-making processes within activities and ensure the pursuit of primary objectives without the encumbrance of protracted physical and mental preparation, which could be exemplified by the Olympics. The prevailing hypothesis suggests a positive relationship between self-efficacy and sporting performance, with the objective of optimising performance in sports (Vieira et al., 2011; Machado et al., 2014). The relationship between self-efficacy, flow and sports performance was investigated by Sklett, Lorås & Sigmundsson (2018) in the context of ski jumping performance.

The present study found that efficacy beliefs have a positive influence on positive thinking, meaning that athletes with higher SE levels have more positive emotions such as happiness, while athletes with lower SE levels show more anxiety and negative thoughts. These results are in line with other findings on self-confidence, flow and self-efficacy perceptions by Gomes et al. (2012).

The objective of high-performance athletes is to avert mental exhaustion resulting from a high training load, which engenders a diminution in self-control during the process of motivational stabilisation. The risk of loss of self-control and elevated anxiety levels in high-performance athletes has been delineated by numerous authors (Baumeister, Vohs & Tice, 2007; Gucciardi et al., 2010). This finding suggests a potential correlation between self-control and willpower, which could be explained by the hypothesis that willpower stabilises the motivational state and self-control simultaneously.

The present results underscore these assumptions (r = .487). Concurrently, a negative correlation is observed between self-control and stress load (r = -.476), aligning with the theoretical approach and the established negative correlation between willpower and stress load (r = -.430). The findings indicate that the reduction of stress load is pivotal to success, as it is anticipated that willpower and self-control will concomitantly increase. The findings also demonstrate a negative correlation between stress load and motor learning performance (r = -.249), which is consistent with the results reported by other researchers. Ehrlenspiel, Wei & Sternad (2010) emphasise that anxiety is a pivotal factor influencing performance in competitive settings, and that this can be addressed through three distinct mechanisms. Firstly, the relationship between experienced anxiety and performance in competition is analysed, then psychological factors are investigated to determine why anxiety has a performance-reducing effect and the question of personality factors that are related to athletic performance and anxiety. However, studies demonstrate that athletes do not suffer from mental illness more frequently than the general population (Rice et al., 2016; Bär & Markser, 2013), although there is a higher risk for injured athletes (Gulliver et al., 2015).

Situations triggered by anxiety and ultimately perceived as negatively stressful have been shown to result in reduced performance (Fletcher, Hanton & Mellalieu, 2006; Mellalieu, Hanton & Fletcher, 2009). Such stress-inducing situations can also be found in the area of organisational support. These can be divided into the areas of sport organisation, sport relationships and inter-personal demands, athletic career and performance, for example, and are of similar importance for both top athletes and non-elite athletes.

CONCLUSIONS

What drives successful athletes to overcome these obstacles and sustain their training and competitive efforts? Ainslie (2021) outlines two possible scenarios that relate to the links between willpower and the reward that comes from potentially achieving a goal. Two scenarios are outlined that either relate to higher level goals or to the suppression of a pattern of behaviour. In the case of higher-order goals, for example, athletes would subordinate themselves to a coach's instruction, even though it may not be in the athlete's best interest but is likely to serve the overarching goal of athletic success. This could be a strenuous strength training session, the training effect of which has a positive impact on competitive performance. The second option suppresses the intention to rebel against a coach's instructions, for example, in order to remain true to one's own intentions. It is clear from the examples given that maintaining willpower is essential for long-term career success, and that its maintenance should be continuously supported by goal coaching measures to avoid stress and possible loss of motivation, as these are inevitably linked to willpower (Ainslie, 2021; Evans, Boggero & Segerstrom, 2016; Konze, Rivkin & Schmidt, 2017).

The results presented here illustrate the need to optimise a dual career, with the support of sport psychology, in order to reconcile the different needs and demands of the partners involved. In particular, the changes in the athlete's personality during a sporting career in relation to their education and the associated changes in needs need to be constantly adapted and reviewed. For example, the GROW model (Whitmore, 2006) can be used for this purpose. It facilitates the regular adjustment of goals and the formulation of possible options

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based on real conditions. Goal coordination defines the will that needs to be present in order to achieve the formulated goals. The GROW model is also well suited for the training of coaches and teachers, who can apply the concept to specific coach-athlete discussions. The aim is to positively influence the dual career by providing optimal psychological support for the athletes and strengthening their self-competence. In particular, the high double burden during school education leads to the need for individual support (Stambulova & Harwood, 2022).

The negative influences on the attitudes of athletes can be described, for example, as an increased number of injuries, loss of schooling, reduced time with family and friends and also increased pressure to perform (Thompson, Rongen, Cowburn & Till, 2022). In particular, coping with increased pressure to perform, which manifests itself at different levels during schooling, needs to be taught by strengthening self-competence.

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ORIGINAL ARTICLE

Effects of an inclusive water polo programme on motor, psycho-pedagogical and social development in deaf-mute adolescents: An experimental study

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ABSTRACT

This experimental study investigates the effectiveness of an inclusive water polo programme on the psycho-physical and social development of deaf-mute adolescents. Twenty-four participants (aged 12-15 years) were divided into an experimental group (n = 12) that followed an adapted water polo programme and a control group (n = 12) that participated in traditional physical education classes. Qualitative analysis revealed that after 10 weeks, the experimental group showed significant improvements in motor performance, perceived self-efficacy and relationship dynamics ($p < .001$). The results confirm the educational and integrative value of sport as a global development tool for people with sensory disabilities.

Keywords: Inclusion, Deaf-mutism, Water polo, Adolescence, Psychophysical well-being, Adapted sport.

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INTRODUCTION

The inclusion of people with disabilities is now a fundamental objective of educational and social policies, as sanctioned by the United Nations Convention on the Rights of Persons with Disabilities (UN, 2006), which recognises the right to full participation in cultural, recreational, sporting and educational life. In this context, the educational and social inclusion of adolescents with sensory disabilities, and deafness in particular, is a crucial and still unresolved challenge, despite the legal and cultural progress made in recent decades (D'Alonzo, 2020; Ianes & Cramerotti, 2021). Deaf-mute adolescents, i.e. children with profound deafness and consequent mutism, often face communication and relational barriers that profoundly affect their psychological, motor and social development (Marschark & Hauser, 2012). The literature documents how communicative isolation can affect self-esteem, self-efficacy and active participation in group life (Convertino et al., 2009; Calderon & Greenberg, 2011). Indeed, a lack of socialisation opportunities can lead to reduced social competence, feelings of exclusion and sometimes psychological adjustment problems (Fellinger et al., 2009; Hintermair, 2013). Sport has been shown to be a powerful catalyst for the overall development of people with disabilities, providing not only physical benefits but also tools for personal and relational growth (Goodwin, 2001; Sherrill, 2004). In particular, adapted sport is configured as an inclusive educational context capable of enhancing individual abilities, stimulating autonomy and promoting peer integration (De Anna, 2009; Messina et al., 2018; Tafuri et al., 2023). Furthermore, inclusive motor practices consistently fit within the pedagogical framework of Universal Design for Learning (UDL), which promotes accessible and flexible environments for all students (CAST, 2018). Among the different sports disciplines, aquatic activities play a privileged role in inclusive education due to their ability to reduce environmental and sensory barriers. Recent studies show that swimming and aquatic activities improve balance, motor coordination, cardiovascular endurance and psycho-emotional well-being, even in people with disabilities (Farì et al., 2023; Morsanuto et al., 2023).

The aquatic environment promotes body awareness, muscle relaxation and experimentation with movements that would otherwise be complex to perform on land, especially for people with sensory or motor disabilities (Carmeli et al., 2003; Geytenbeek, 2002). Water polo, as a team sport played in water, combines the benefits of aquatic activities with the cooperative dimension typical of collective sports. It requires strategies of non-verbal communication, motor synchronisation, spatial management and group awareness - all skills that can be adapted to promote the inclusion of people with deafness (Dervishaj et al., 2020; Gualdi-Russo et al., 2021). In addition, the playful-competitive component of water polo can stimulate a sense of belonging, motivation and resilience, fundamental aspects in the adolescent growth trajectory (Weiss & Ferrer-Caja, 2002; Eime et al., 2013). Despite this potential, the scientific literature has mainly focused on individual disciplines or generic sports programmes for people with hearing impairments, neglecting the systematic analysis of the effects of an aquatic team sport such as water polo. Existing studies highlight the cognitive and psychological benefits of sport participation, but rarely focus on group dynamics, peer interaction and positive identity building in aquatic sport contexts (Block, 2007; Haegele & Sutherland, 2015).

One of the key concepts underlying sport inclusion is 'self-efficacy' (Bandura, 1997), i.e. the perception of one's ability to act effectively in specific contexts. The literature shows that high self-efficacy is associated with higher participation, better school adjustment and higher subjective well-being, even among people with disabilities (López-Pérez et al., 20-21; Huang & Chang, 2009). Similarly, positive social relationships with peers are an important predictor of developmental psychological well-being, especially for adolescents with special educational needs (Asher & Parker, 1989; Avramidis, 2013). With this in mind, the present study aims to fill a gap in the literature by systematically investigating the effects of an inclusive water polo programme on a group of deaf-mute adolescents, focusing on three developmental dimensions: (1) motor skills

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(endurance, coordination, agility), (2) perceived self-efficacy, and (3) social integration among peers. The proposed intervention is based on an integrative pedagogical model in which movement is not only a vehicle for physical skills, but also a tool for relationships, expression and mutual recognition (Trabalzini, 2020; Vayer, 1986). The work fits into a multidisciplinary theoretical perspective, drawing on special education, developmental psychology, adapted motor activity theory and studies on inclusive educational practices. The hypothesis underlying the research is that participation in an adapted water polo programme, conducted with inclusive methodologies and mediated by communicative technologies (LIS, visual aids), can produce significant improvements in the three dimensions studied, compared to a control group engaged in traditional motor activities. The approach adopted is experimental, with pre- and post-intervention measurements to ensure methodological rigour and reliability of results. The aim is not only to demonstrate the effectiveness of a specific programme, but also to contribute to pedagogical and scientific reflection on the use of sport as an educational resource for inclusion. In the light of the results, it will be possible to formulate operational recommendations for educators, coaches, school managers and sports centre managers interested in promoting evidence-based inclusive practices.

METHODS AND TOOLS

Research drawing

The present study adopts a controlled experimental design with pre- and post-tests, based on a qualitative-quantitative comparative approach, to verify the effects of an inclusive water polo programme on three developmental dimensions: motor, psycho-pedagogical and social. The design follows the logic of a "*randomised controlled trial*" (RCT), albeit with a limited number of participants, typical of pilot studies in the field of inclusive education (Robson, 2011; Cohen, Manion & Morrison, 2018). This approach allows observed changes to be more confidently attributed to the intervention used, reducing bias from external factors. The experimental design was chosen because it allows for a direct comparison of the quantitative and qualitative results obtained by an experimental group, which received the specific intervention (inclusive water polo programme), and a control group, which continued with standard school motor activities without any adaptations. Qualitative-quantitative data were collected at two points in time: before the start of the intervention (T1) and at the end of ten weeks (T2). The dependent variables were selected based on the existing literature on evaluating the effectiveness of adapted sport (Sherrill, 2004; Block & Obrusnikova, 2007; DePauw & Gavron, 2005). Methodological rigour was maintained through the randomisation of participants, the use of validated instruments and the use of external evaluators with expertise in hearing impairment, thus minimising the observer effect (Roulston, 2010).

Participants

The sample consisted of 24 deaf-mute adolescents (13 females, 11 males), aged between 12 and 15 years (M = 13.1; SD = 1.2), recruited from two inclusive secondary schools in the Campania region. The criteria for inclusion in the study were:

- Diagnosis of severe or profound bilateral sensorineural deafness certified according to ICD-10 criteria.
- Language competence in LIS (Italian Sign Language) as a first language.
- Basic swimming autonomy, verified by a preliminary test with FIN certified instructors.
- No associated severe cognitive impairment or relevant neurological comorbidity.
- Informed parental/guardian consent and approval by the relevant university ethics committee.

The choice of target population reflects the need to provide meaningful physical activity opportunities to individuals who are often excluded from traditional physical activity programmes (Lieberman et al., 2004;

Marschark & Hauser, 2012). Participants were randomly allocated to the two groups using a computerised randomisation system, stratified by gender and school affiliation. This ensured initial homogeneity between the groups. The activities of the experimental group took place in a sports centre equipped with a regulation indoor swimming pool (25 m, 6 lanes), approved for Paralympic activities and accessible to people with disabilities. The sessions took place during non-school hours, in a protected environment without architectural barriers, with adapted changing rooms and specialised staff. The control group continued the motor activities planned in the school curriculum in their respective gymnasiums, supervised by their physical education teachers.

Intervention

The inclusive water polo programme was developed over a 10-week period, with two weekly sessions of 90 minutes each. The intervention was designed according to the principles of universal design for learning (UDL) and adapted sport, emphasising active participation, collaboration and personalisation of goals (Moran & Block, 2010; Haegele & Sutherland, 2015). General programme aims:

- To promote the improvement of functional motor skills and aquatic coordination.
- To increase self-efficacy and emotional resilience.
- To promote peer social interaction in cooperative contexts.

Each session followed a structured, recurring pattern:

1 Warm-up (15 minutes)
- Global joint mobility.
- Dynamic stretching and cardiovascular warm-up in shallow water.
- Ball games.

2 Technical activities (30 minutes)
- Basic swimming and floating techniques.
- Balls, passes and throws with visual and tactile adaptations.
- Simulations with facilitating rules

3 Situational games (30 minutes)
- 3 vs 3 mini-matches with LIS referees.
- Co-operative relays.
- Exercises with alternating roles (goalkeeper, centre-back, defender).

4 Defatigue and metacognition (15 minutes)
- Stretching in the water and guided relaxation.
- Group reflection supported by visual posters and marked dialogue.
- Visual experiential diary (pictograms, icons, drawings).

The adaptations concerned both the environment and the teaching, in line with the recommendations of the European Agency for Special Needs and Inclusive Education (2018):

- Visual signs in the pool.
- Bilingual instructors (Italian/LIS).
- Extended learning times.
- Immediate and multimodal feedback (visual, tactile).
- Personalised monitoring of skills.

The control group continued with the general motor activities provided for in the school curriculum (free body exercises, non-adapted team games) under the guidance of the physical education teachers. No specific

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interventions or forms of adaptation or communicative support were used. This allowed a "*naturalistic*" comparison of the effects of the adapted programme.

Evaluation tools

The selection of instruments for quantitative analysis was guided by criteria of validity, reliability and adaptability to an inclusive context with deaf-mute subjects. All tests were administered by operators experienced in motor and augmentative communication.

Performance

25 metres Swimming Test

The time taken to cover 25 metres in freestyle. Electronic chronometric measurement. Validated for developmental age (Caspersen et al., 1985; Zinner et al., 2015).

Water Jump Test from a static position

Measures the explosive power of the lower limbs in an aquatic environment. Height measured in cm using underwater photocells. Adapted from the Sargent Jump Test (Harman et al., 1990).

Psycho-Pedagogical Well Being

General Self-Efficacy Scale (GSES)

English version of Sibilia et al. (1995). 10-item scale, Likert 1-4. Reliability: $\alpha = 0.86$. The instrument was adapted in LIS format by means of visual aids validated by experts.

Social Inclusion

Peer Interaction Scale (PIS) – Adapted version

Measures the quality of peer interactions in school and sports contexts (Asher et al., 1979). Adapted for individuals with sensory disabilities by Bossaert et al. (2011).

All instruments were adapted and validated through a process of visual translation into LIS, supported by a team of interpreters, developmental psychologists and educators with expertise in deafness. The tests were preceded by familiarisation sessions on the methods of administration. Responses were collected in the presence of LIS mediators to ensure the authenticity of the data and reduce the risk of semantic misunderstandings (Napier & Leeson, 2016). For the qualitative analysis, semi-structured interviews and visual experience diaries collected from both groups were analysed using NVivo 14 software. The analysis followed the steps of Braun and Clarke's (2006) thematic approach: familiarising with the data, generating initial codes, exploring themes, reviewing, defining and naming themes.

Statistical analysis

Analyses were performed with SPSS v27 using a mixed approach:

- Repeated measures analysis of variance (ANOVA) (time × group) to compare the evolution in the two groups.
- In case of significant interaction, t-tests were performed for paired (within group) and independent (between groups) samples.
- Calculation of effect size by:
    - Partial η^2 (ANOVA),
    - d di Cohen (**t**-test), according to Cohen's criteria (1988):

$$d = 0.2 \text{ (small)}, 0.5 \text{ (moderate)}, 0.8 + \text{ (large)}.$$

- Testing of statistical assumptions: normality (Shapiro-Wilk), homogeneity of variances (Levene), sphericity (Mauchly).

Statistical significance was set at $p < .05$, but practical significance was also considered, which is particularly relevant in educational contexts (Greenhalgh et al., 2016).

RESULTS

Quantitative results analysis

The Experimental Group showed statistically significant improvements in all variables analysed.

Table 1. Quantitative results experimental group.

Variable	Pre-test (M ± DS)	Post-test (M ± DS)	*p*	d
Time 25m (s)	37.1 ± 2.9	30.8 ± 2.6	<.001	1.45
Jump in the water (cm)	22.7 ± 3.5	29.1 ± 3.3	<.001	1.33
Self-Efficacy (GSES)	21.5 ± 3.1	30.2 ± 2.9	<.001	1.80
Peer Interaction (PIS)	14.8 ± 2.6	21.7 ± 2.4	<.001	1.82

Performance

The results from the experimental group (EG) show significant improvements in motor skills. The mean time to swim 25 metres in water decreased from 37.1 ± 2.9 seconds to 30.8 ± 2.6 seconds ($p < .001$), indicating an increase in swimming efficiency. In addition, water jump height increased from 22.7 ± 3.5 cm to 29.1 ± 3.3 cm ($p < .001$), suggesting an improvement in explosive strength and neuromuscular coordination. These results are consistent with previous studies that have highlighted that regular physical activity promotes growth and development in childhood, with benefits for physical, mental and cognitive health. In addition, participation in physical activity can support children's social development by providing opportunities for personal expression and social integration.

Psycho-Pedagogical Well-Being

Perceived self-efficacy, as measured by the General Self-Efficacy Scale (GSES), increased significantly in the EG from 21.5 ± 3.1 to 30.2 ± 2.9 ($p < .001$). This increase reflects an improvement in perceived ability to cope and overcome challenges. The literature shows that sport has important intrinsic qualities that enable social, psychological and physical development in an individual, such as improved self-esteem and independence in performing daily tasks. In addition, regular physical activity during childhood tends to become an integral part of a person's lifestyle, which has a positive impact on health in later life.

Social Inclusion

Peer interaction, as assessed by the Peer Interaction Scale (PIS), showed a significant improvement in the EG, increasing from 14.8 ± 2.6 to 21.7 ± 2.4 ($p < .001$). This result indicates an improvement in the participants' social and interpersonal skills. Previous studies emphasise the importance of inclusion in school sport, showing that participation in physical education provides a high level of acceptance and recognition for children or young people with disabilities, even outside of sport. In addition, physical activity can have a positive impact on several aspects of young people's lifestyles, encouraging the adoption of healthy behaviours.

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Control Group

In the control group (CG), which continued to perform general motor activities as part of the weekly school programme without any specific adaptations, there were no statistically significant differences in any of the variables analysed. This comparison confirms the effectiveness of the inclusive water polo programme in promoting the motor, psychoeducational and social development of deaf-mute adolescents. In the control group (CG), which continued with unadopted physical education activities at school, no statistically significant changes were observed between pre- and post-test measurements. The detailed quantitative results are detailed in Table 2.

Table 2. Quantitative results control group.

Variable	Pre-test (M ± DS)	Post-test (M ± DS)	p	d
Time 25m (s)	36.9 ± 3.1	36.3 ± 3.0	n.s.	0.19
Jump in the water (cm)	22.9 ± 3.2	23.1 ± 3.0	n.s.	0.06
Self-Efficacy (GSES)	21.2 ± 2.9	21.6 ± 3.1	n.s.	0.13
Peer Interaction (PIS)	14.7 ± 2.5	15.0 ± 2.6	n.s.	0.12

Note. n.s. = not significant. Effects of negligible magnitude according to Cohen's criteria.

These data confirm that simply continuing school physical activity without specific adaptations was not sufficient to promote improvements in the dimensions studied.

Quantitative analysis revealed significant differences between the experimental group (EG) and the control group (CG) in all variables studied. The EG showed significant improvements in motor performance, perceived self-efficacy and peer interaction, whereas the CG showed no statistically significant changes.

Qualitative results analysis

Qualitative thematic analysis was conducted using NVivo 14 software on semi-structured interviews and visual experience diaries collected from both groups. Qualitative sample:

- EG: 12 participants→ 12 interviews + 12 visual diaries.
- CG: 12 participants → 8 interviews (4 declined) + 12 less detailed visual diaries.

Table 3. Qualitative results.

Theme	Description	Frequency	EG	CG
Empowerment and mastery	Expressions related to feeling capable, useful, competent.	High	XXX	-
Effective non-verbal communication	Use of looks gestures and facial expressions to cooperate.	High	XXX	-
Group cohesion and sense of belonging	Feeling part of the team, accepted.	High	XX	-
Boredom and routine	Perception of repetitive or unstimulating activities.	Average	-	XX
Autonomy and personal initiative	Experiences in which participants report greater decision-making autonomy.	Average	XX	-
Communication frustration	Difficulty expressing oneself in motor contexts.	High	-	XXX

Emerging themes:
These themes were systematically coded and compared between groups, revealing a clear advantage for the EG in terms of psycho-pedagogical well-being, motivation and social interaction.

Samples of text extracts (EG)

- I like that we can understand each other without words. Everything is different under water, but we understand each other.
- I used to be afraid of making mistakes, but now I try even if I'm not sure. The water helps me.

Samples of text extracts (EG)

- We always do the same things in the gym and I don't always understand what to do.
- The others talk and I can't keep up, so I do it myself.

DISCUSSION

The results of the study strongly support the initial hypothesis: a structured inclusive water polo programme can have significant positive effects on the motor, psychoeducational and social development of adolescents with deafness. These data are in line with the literature that identifies adapted sport as a powerful mediator of well-being and inclusion (DePauw & Gavron, 2005; Goodwin & Watkinson, 2000). Firstly, analysis of motor performance - both in terms of swimming speed over 25 metres and jumping height in the water - shows a clear increase in neuromuscular efficiency. This improvement can be attributed to regular training, the specificity of the motor tasks and the aquatic environment, which has the advantage of reducing joint stress and facilitating wide, harmonious movements (Franceschini et al., 2022). As noted by Getz, Hutzler and Vermeer (2006), aquatic activities allow for proprioceptive and vestibular stimulation, which promotes motor development in individuals with sensory disabilities and provides a safe but challenging exercise environment. On a psychological level, the significant increase in perceived self-efficacy (measured by the General Self-Efficacy Scale) should also be interpreted as an indicator of the empowerment generated by the sporting context.

According to Bandura (1997), a sense of self-efficacy is built through successful experiences, social models, verbal persuasion and physiological regulation: all elements that are present in the proposed programme, thanks to the systematic use of visual and physical reinforcement, the presence of competent models (LIS coaches) and the opportunity to face progressive and calibrated challenges. Furthermore, the specific adaptive framework of the intervention, based on equal access and the valorisation of differences, allowed the participants to experience feelings of competence and mastery, which are central to adolescent identity development (Deci & Ryan, 2000). One of the most significant findings relates to the improvement in relational dynamics. Scores on the Peer Interaction Scale increased significantly in the experimental group, indicating a greater capacity for positive peer interaction. This finding reflects the assumption of inclusive education that collaboration in meaningful activities is a powerful driver for building social bonds (Booth & Ainscow, 2011). In particular, water polo - with its demands for cooperation, synchronisation and instant adaptation - promotes forms of communication that are alternatives to verbal language, such as gestures, eye contact and proxemics, tools that are already familiar to deaf people.

As shown by Lieberman et al. (2004), non-verbal communication in sport can act as a communicative 'bridge' that allows language barriers to be overcome and authentic interaction to flourish. It should also be noted that the improvement recorded in the experimental group did not occur in the control group, confirming the specificity of the intervention, where participants expressed feelings of monotony, communication difficulties

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and poor integration, confirming that generic school motor activities are not sufficient to meet the educational and relational needs of students with sensory disabilities. This suggests that normal school physical activities, unless adapted, are not sufficient to significantly promote the developmental dimensions investigated. This point is particularly relevant from a systemic perspective, as it highlights the urgent need for further training of physical education teachers in relation to the specific needs of students with sensory disabilities (Rouse, 2008). From a pedagogical point of view, the success of the intervention can be attributed to the inclusive structure of the programme, the training of the operators and the use of multimodal and cooperative strategies. These results support the idea that physical education should be rethought in an inclusive and relational way, valuing physicality as a vehicle for expression, learning and belonging. From a methodological point of view, the use of validated tools adapted to the context of deaf people ensured the reliability of the measurements.

The use of experienced LIS operators avoided the risk of misunderstandings and communication biases during the test phases. Furthermore, the experimental approach with a control group and pre-post measurements allows a high degree of confidence in attributing the observed changes to the intervention. A limitation of the study is the sample size, which, although sufficient to ensure statistical power for the analysis, could be increased in future research for greater generalisability. In addition, the 10-week duration, although significant, does not allow for the verification of long-term effects. A follow-up after six months or a year would be desirable to understand whether the observed improvements are sustained over time. Another point for reflection concerns the role of the trainers. Their competence in LIS and pedagogical sensitivity were key factors in the success of the project. This underlines the need for multidisciplinary training for sports professionals that goes beyond technical skills to include communication and interpersonal skills (Sherrill, 2004).

Finally, it should be emphasised that inclusive sport activities not only benefit students with disabilities but can also transform the whole educational context into a more empathetic, collaborative and diversity-conscious environment. As Morin (2001) states, education must embrace the complexity of the human condition and recognise the educational value of difference and intercultural dialogue. Looking ahead, extending the study to larger samples and different contexts could strengthen the generalisability of the findings. In addition, medium- and long-term follow-up will allow the stability of the induced changes to be assessed. The combination of an experimental and qualitative approach represents a promising methodological model for future research in inclusive education.

CONCLUSIONS

This research has contributed to enriching the landscape of studies on inclusion in education and sport, providing empirical evidence to support the effectiveness of an adapted water polo programme for deaf-mute adolescents. In particular, it has shown that structured, accessible and moderately communicative physical activity can have a positive and significant impact on three fundamental axes of human development: functional motor skills, psychological self-efficacy and interpersonal skills. The main contribution of the study is that it focuses not only on the improvement of motor skills, but also on the educational, social and emotional effects of the sport experience. This holistic perspective is in line with the biopsychosocial approach to disability proposed by the World Health Organisation (WHO, 2001), which goes beyond the medical-centred model to value the potential of the person in their environment. From an operational point of view, the findings suggest that inclusive sport programmes should become an integral part of the curriculum in lower secondary schools, especially those with an inclusive vocation.

International guidelines (UNESCO, 2015; European Agency for Special Needs and Inclusive Education, 2020) emphasise the importance of providing equal opportunities for all students to participate in physical activity and sport, regardless of their starting conditions. Water polo, as a dynamic, cooperative sport that can be practised in a supportive environment such as water, is one of the most promising disciplines for the inclusion of young people with deafness. Its communicative nature, which requires the reading of body signals and constant adaptation to partners and opponents, makes the game a situated, experiential and highly relational learning space (Vygotsky, 1978). In addition to the aspects highlighted above, the symbolic value of the initiative should be emphasised: offering young people, who are often excluded, the opportunity to practise a competitive team sport, traditionally considered "*difficult*", produces an identity transformation that goes far beyond the technical skills acquired. It is an authentic claim to belonging and to the right to the complexity of human experience (Nussbaum, 2011). In this sense, the results invite educational and sports institutions to build stable networks of collaboration between teachers, educators, sports instructors and families, with the aim of creating multisensory, accessible and challenging educational environments.

It is not enough to simply 'integrate' students with disabilities: the whole education and sports system needs to be rethought in terms of inclusivity, changing rules, methods, expectations and spaces. In the future, we hope to extend the study to different contexts (urban and rural areas, different school levels) and to multiple or different disabilities (hearing impairment, intellectual disability, autism spectrum disorders) in order to test the adaptability of the proposed model. A parallel qualitative analysis is also desirable, using interviews or focus groups to explore the experiences of participants, capturing their emotions, meanings and narratives. Finally, a strong investment in the professional training of sport educators is recommended, so that skills such as LIS, diversity management, inclusive education and adaptive design become an integral part of university and professional courses. Inclusive sport is not just an educational practice: it is a worldview based on fairness, respect and recognition of the unique value of each person.

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The authors noted that there was equal participation in the elaboration of this document.

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ORIGINAL ARTICLE

Reliability and contributing factors to a newly developed reactive agility test performance

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ABSTRACT

This study assessed the intra-session reliability and the impact of cognitive and physical factors on the performance of a newly developed Triple Y reactive agility test (3YRAT). Twenty-eight male soccer players (12.74 ± 0.93 years, 161.14 ± 13.46 cm, 49.81 ± 9.73 kg) completed the 3YRAT, visual inhibition task (Go/No-go), choice reaction test, and 10 m sprint test. The 3YRAT demonstrated good reliability (ICC = 0.85 with 95 % CI = 0.71-0.93; CV = 2.3 %; SEM = 0.31s; MDC = 0.85s). The time in 3YRAT was significantly correlated with 10 m sprint time (r = 0.74, $p < .001$), and the response times in cognitive tests (Go/No-go: r = 0.48, $p = .01$; choice reaction: r = 0.41, $p = .03$). Regression analysis found that acceleration sprint speed decision-making, and visual inhibition were the significant predictors of 3YRAT performance, explaining 70 % of the variance ($R^2 = .70$). Overall, both motor (38 %) and cognitive components (32 %) significantly contributed to the 3YRAT performance. This study introduced a new and reliable procedure for assessing reactive agility in youth soccer players, which could be applicable to other athletes of "*agility-saturated*" sports. This test represents a compromise between force- and velocity-oriented changes of direction, balancing the demands on perceptual-cognitive skills and motor abilities in reactive agility tasks.

Keywords: Performance analysis, Sports performance, Open-skill agility, Cognitive component, Motor component, Team sports.

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INTRODUCTION

Recent research has shown that one of the most crucial factors influencing athletes' performance in invasive sports is their change of direction speed in response to a visual stimulus, commonly referred to as reactive agility (Frederick et al., 2020; Hassan et al., 2022; Munivrana et al., 2022; Pojskic et al., 2018; Trajković et al., 2020). Reactive agility encompasses both motor components (such as linear sprint speed and leg muscle qualities) and cognitive elements of performance (Young et al., 2015). In many studies, only the cognitive aspect of reactive agility has been effective in distinguishing higher-level athletes from their lower-level counterparts (Farrow et al., 2005; Gabbett et al., 2008; Serpell et al., 2010; Sheppard et al., 2006). Several authors have aimed to design a reactive agility test tailored to the specific demands of various sports (Frederick et al., 2020; Krolo et al., 2020; Munivrana et al., 2022; Sekulić et al., 2017; Sinkovic et al., 2023). Despite advancements in diagnostic methods and devices, creating practical tests that reflect real-game situations including time restricted problem solving and the pressure from opponents remains challenging. To improve the ecological validity of reactive agility testing, some researchers recommend using a "*human stimulus*" instead of a reaction to lights (Gabbett et al., 2008; Chaalali et al., 2016; Spiteri et al., 2012; Trajković et al., 2020). Although tests that involve live testers demonstrate good reliability, the variability in their movements can affect the overall agility score (Young and Willey, 2010). Video-based specific stimuli have been shown to be a suitable alternative (Farrow et al., 2005; Serpell et al., 2010; Young et al., 2011). Notably, a study by Young et al. (2011) revealed that using sport-specific video-based stimuli in reactive agility tests can more effectively differentiate higher-skilled athletes from lower-skilled ones compared to light-based stimuli. However, reactive agility tests utilizing light stimuli have also successfully categorized two performance-level groups (Lockie et al., 2014; Pojskić et al., 2018).

A review by Morral-Yepes et al. (2022) on reactive agility testing in team sport players found that 75 % of studies utilized tasks such as Y-shaped or T-shaped movements. Light and human stimuli were the most common in them while video stimuli were used less frequently. Most studies required athletes to execute a single change of direction at angles of either 45 or 90 degrees over distances ranging from 7 to 12 meters. These types of reactive agility tests have been employed in various sports, including basketball (Horníková and Zemková, 2022; Jeffriess et al., 2015; Lockie et al., 2014; Scanlan et al., 2014), rugby (Green et al., 2011; Serpel et al., 2010), netball (Cochrane, 2013), soccer (Chaalali et al., 2016; Fiorilli et al., 2017), handball (Spasić et al., 2015), and Australian football (Henry et al., 2011; Young et al., 2011). However, this reactive agility testing insufficiently evaluates the cognitive aspects of performance, since the decision-making processes generally occur in a simplified context where participants make a single response with only two available options (Horníková and Zemková, 2022). Moreover, it seems that low correlation appears between total agility time and choice reaction time when the general cognitive functions measured by the laboratory-based tests are used (Matlák et al., 2024). Sekulić et al. (2014) introduced reactive agility test named "*Stop´n´go*" (SNG-RAT) requiring multiple changes of direction to visual stimuli including moments of zero velocity. For instance, the reactive agility test with stop-and-go movement patterns (SNG-RAT) has been widely used in soccer (Pojskic et al., 2018) and other "*agility-saturated sports*" (Sattler et al., 2015; Sekulić et al., 2014). The SNG-RAT involves repetitive responses to four possible answers. In the study by Born et al. (2016), players performed 9 sprints with varying cutting angles (10° - 180°) and distances in response to visual stimuli. The increased number of options increases the demands on decision-making ability, which, along with physical and technical factors, influences reactive agility performance (Young et al., 2015).

The contribution of the cognitive component is typically calculated as the difference between the reactive and preplanned versions of the same test (Fiorilli et al., 2017; Popowczak et al., 2021). Alternatively, it can be assessed using psychological tests (Pavlinović et al., 2024) or reaction time tests (Horníková and Zemková,

2022). The contribution of the motor component to performance in reactive agility tests can be analysed by examining its relationship with linear speed and change of direction speed (Horníková and Zemková, 2022; Horníková et al., 2021; Chow et al., 2022; Krolo et al., 2020; Pojskic et al., 2018; Popowczak et al., 2021). While a significant influence of motor factors has been frequently identified (Krolo et al., 2020; Pojskic et al., 2018; Popowczak et al., 2021), there remains a lack of tests that adequately reflect cognitive factors.

The number of sport-specific reactive agility tests is steadily increasing; however, there remains a relatively small number of general tests suitable for a broader range of athletes across different team sports. The aim of this study was to develop a reliable test that would be useful in practice when comparing the reactive agility performance of players of different sports. The aim of this study was to adapt the test to the requirements of team sports in terms of distance covered as well as the type of performing changes of direction (under different angles) and a more pronounced contribution of the cognitive component compared to the most commonly used Y-shaped type of test. The reactive agility test employed in this research utilized light-based visual stimuli, requiring participants to perform correct movement responses while combining non-stop running with stop-and-go actions during the change of direction. This newly developed test, named the Triple Y reactive agility test, has not been used in any prior studies. Thus, the objectives were twofold: 1) to investigate the intra-session reliability and construct validity of the Triple Y reactive agility test among soccer players, and 2) to identify the factors that contribute to its performance. Although reliability was assessed in young soccer players, this test has the potential to be suitable for athletes in various other invasive sports. Improving the evaluation of reactive agility performance may help practitioners to identify crucial aspects of sport performance and facilitate talent identification in invasive sports.

MATERIAL AND METHODS

Participants

A total of twenty-eight male youth soccer players participated in this study (12.74 ± 0.93 years, 161.14 ± 13.46 cm, 49.81 ± 9.73 kg). They had an average of 4.93 years (±1.84) of soccer-specific organised training experience. Using G*Power software (Version 3.1.9.7, Institut für Experimentelle Psychologie, Düsseldorf, Germany), we calculated the necessary sample size for linear multiple regression, which determined that an optimal sample size of 25 participants was required (effect size = 0.50, power (1-β) = 0.90, significance level α = .05). Our sample size increased the power to 0.96. The inclusion criteria for this study were as follows: participants had to be active soccer players who regularly attended training sessions and matches, with a minimum of one year of experience. Additionally, they must not have suffered any injuries in the last three months. Goalkeepers and players who do not train consistently were excluded from the study. All soccer players participating in the study had a similar training volume, attending three training sessions per week. All of them were informed of the risks and benefits of participation, and written informed consent was obtained from them and their legal guardians prior to the testing. The study was conducted in accordance with the ethical regulations for research, approved by the Ethics Committee of Comenius University in Bratislava, Faculty of Physical Education and Sport (No. 2/2023) in accordance with the latest version of the Helsinki Declaration.

Procedures

This study conducted a cross-sectional analysis involving youth soccer players. After familiarization and personal data collection, the participants completed two cognitive tests indoors: the visual inhibition task (Go/No-Go test) and the choice reaction test. Afterwards, they moved outside to an artificial grass soccer field and performed a 15-minute warm-up that included light jogging, dynamic stretching, running-specific drills, and short sprints. Then they performed the reactive agility test (3YRAT) and a 10-meter sprint test. All

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tests were carried out using the Sportreact system, which was connected to a mobile application (Sportreact, Zagreb, Croatia). This system includes six photoelectric sensors and LED screens that display different signs and colours, allowing the sensors to function as either single-beam timing gates or proximity sensors. Tests including reactions to the visual stimuli (cognitive tests and 3YRAT) were performed in three trials. Since we expected a learning effect after the first trial, we did not record its value, and it was intended only as a practice trial. According to Zemková and Hamar (2001), this effect should disappear after the third trial. Therefore, we considered three trials sufficient.

Go/No-go test (visual inhibition task)

The Go/No-Go test, which assesses response inhibition, is one of the predefined tests in the Sportreact application. We designed a modified version using four light photocells arranged in a line, spaced 10 cm apart, and set at approximately chest height for the participant. The test begins with a countdown from the main photocell (5-4-3-2-1), after which the first stimulus appears. The stimulus is either a green light ("*go*" signal), indicating that the participant must respond using their dominant hand, or a red light ("*no-go*" signal), indicating that the participant should not respond. If the participant does not respond within two seconds, the signal disappears. When he responded to the signal "*no-go*," the photocells did not react. The test consists of 20 stimuli presented in random order, with a random generation time between 500 and 1000 ms between the signals. The ratio of "*go*" to "*no-go*" signals is consistent for each participant, set at 11 "*go*" signals to 9 "*no-go*" signals. One visual demonstration and practice trial were carried out. After that, participants undergo two trials with 2 min recovery between them. The result is the shorter total duration of the test taken for the two trials. The intra-session reliability showed to be moderate (ICC = 0.623).

Choice reaction test (decision-making)

The photocells were set up in the same manner as in the previous Go/No-Go test. This was the predefined neurocognitive test within the Sportreact mobile application, which was modified for our study. After a countdown, all four photocells lit up. One of the signals was always either a red "*X*" (indicating that the participant should respond with their right hand) or a blue "*O*" (indicating that the participant should respond with their left hand), presented in equal ratios. A total of 32 stimuli appeared in random order, with a random generation time between 500 and 1000 ms. The examiner monitored the participants to ensure that each response was made with the correct hand. Participants were instructed to respond carefully to minimize incorrect responses. When the incorrect response was observed, the new trial must be performed. One visual demonstration and practice trial were carried out. After that, two trials with 2 min recovery time between them were conducted. The result of the test is the shorter total duration of the test taken for the two trials. The intra-session reliability showed to be moderate (ICC = 0.715).

Triple Y reactive agility test (3YRAT)

The structure of the Triple Y reactive agility test (running distance, angles of changes in direction) was adapted to mimic the demands of several team sports. It consists of 5+10+10+5-meter sprints that incorporate changes of direction at the angles of 30° (three times) and 180° (three times). It is a combination of a velocity- and force-oriented reactive agility test, given that both stop-and-go and non-stop running scenarios are included.

The sensors were arranged as illustrated in Figure 1. Participants began the test 50 cm behind the starting line, positioned in the centre of a timing gate formed by two sensors (labelled No. 0 and 1) facing each other. This timing gate served as a trigger point for the additional light signals generated by sensors No. 2 to 5. As soon as a participant crossed the middle gate, the sensors would light up green. Participants had to cross the middle gate three times, following these steps: 1) accelerate, change direction toward the green lit sensor

that is lit green, and deactivate it by bringing their hand within 20 cm distance; 2) run back through the middle gate and change direction according to the lit sensor on the opposite side; 3) run back again, deactivate the last sensor, and return to the middle gate. The test finishes after the final crossing of the middle gate. Two trials were conducted with predefined sequences (2-4-3, 3-5-3) after one practice trial (3-5-2). The outcome of the test was the shorter total time recorded from the two trials.

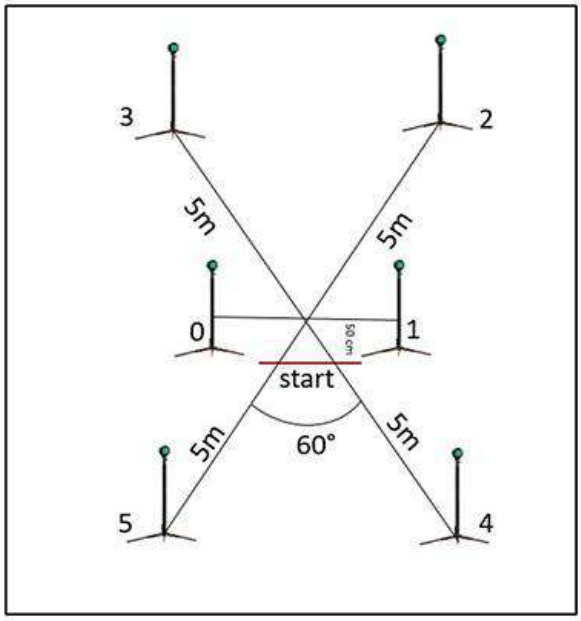

Figure 1. Triple Y reactive agility test.

10m sprint test

The 10-meter sprint test evaluates linear acceleration speed. In this test, participants were required to cover a distance of 10 meters between two pairs of photocells as quickly as possible. Each participant started from a line positioned 0.5 meters behind the starting photocells. Participants completed two trials with a one-minute rest interval between them. The test was measured using Sportreact (Zagreb, Croatia), which has an accuracy of 0.001 seconds. The final result was recorded as the fastest time from the two trials, measured in seconds.

Statistical analysis

Data analysis was conducted using SPSS version 23.0 for Windows. The Shapiro-Wilk test confirmed the normal distribution of data. Intra-session reliability (trial-to-trial) of the Triple Y reactive agility test was assessed by calculating Intraclass Correlation Coefficient (ICC) using the ICC (3,1) model, applying a two-way mixed effects approach, absolute agreement, and single measures (Koo and Li, 2016). Reliability was classified as follows: fair (0.25–0.50), moderate (0.50–0.75), good (>0.75), and excellent (>0.90; Portney, 2020). The absolute reliability of the Triple Y test was expressed as the within-subject coefficient of variation (CV), which was also used to determine the magnitude of measurement error. A CV of ≤ 10 % was deemed acceptable (Uthoff et al., 2018). The paired t-test was used to find the differences between the first and second trials. To visually analyse the differences between Trial 1 and Trial 2, a Bland-Altman plot with a 95 % confidence interval (95 % CI) was generated. Additionally, the minimal detectable change (MDC) was calculated using the standard error of measurement (SEM) to emphasize its practical application using the following formulae:

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$$SEM = SD \times \sqrt{(1 - ICC)}$$

$$MDC = 1.96 \times \sqrt{(2)} \times SEM$$

A paired sample t-test was conducted to determine whether significant differences existed in the mean times between test trials. Pearson's correlation analysis was employed to examine the relationships between reactive agility time (the dependent variable) and independent variables (times from the Go/No-Go test, choice reaction task, and 10 m sprint time). The magnitude of the correlation was interpreted according to the following scale: 0.1 or less = trivial, greater than 0.1 to 0.3 = small, greater than 0.3 to 0.5 = moderate, greater than 0.5 to 0.7 = large, greater than 0.7 to 0.9 = very large, and greater than 0.9 to 1.0 = almost perfect (Hopkins, 2009). Multiple regression analysis (using the enter method) was performed to identify the predictor variables for Triple Y reactive agility performance. Variance inflation factor was used to detect multicollinearity in multiple regression model. The significance level was set at $\alpha = .05$.

RESULTS

The mean score (±SD), and coefficient of variation (CV) for all tests are presented in Table 1.

Table 1. Test results of cognitive, reactive agility, and speed tests.

Test	Time [s]	CV
Go no-go test	29.76 ± 0.63	2.0 %
Choice reaction test	51.00 ± 3.67	7.2 %
3YRAT	10.46 ± 0.77	7.4 %
10 m sprint test	2.10 ± 0.18	8.4 %

Intra-session reliability of the Triple Y reactive agility test

The paired samples t-test did not show a significant difference between the two trials (t = 0.92, *p* = .37). The mean score for the 3YRAT obtained from both trials conducted on the same day, along with the ICC 95 % confidence intervals, percentual values of CV, SEM, and MDC are summarized in Table 2. The intra-session reliability of the 3YRAT was assessed using the ICC. The analysis revealed an ICC value of 0.85 (0.71 - 0.93 95% CI), indicating good reliability. The SEM was 0.31 s, corresponding to 2.87 % of the mean test result. The MDC was calculated as 0.85 s, equivalent to 7.96 %, suggesting that any change greater than 0.85 s can be considered a real change beyond measurement error. The CV was 7.43 %, which is generally considered acceptable for performance tests. Thus, the agility test demonstrates satisfactory reliability for intra-session performance assessment.

Table 2. Intra-session reliability statistics of the Triple Y reactive agility test.

Test	Trial 1 [s]	Trial 2 [s]	ICC (95% CI)	CV	SEM	MDC
3YRAT	10.67 ± 0.83	10.59 ± 0.76	0.85 (0.71-0.93)	7.43 %	2.87 %	7.96 %

Note: ICC – Intraclass correlation coefficient; CV – Coefficient of variation; SEM – Standard error measurement; MDC – Minimal detectable change).

The Bland-Altman plot in Figure 2 illustrates the agreement between Trial 1 and Trial 2. The chart indicates that most of the differences fall within the 95 % agreement limits, which range from -0.78 s to 0.93 s, with only 1 out of 30 data points (3.3 %) lying beyond these limits.

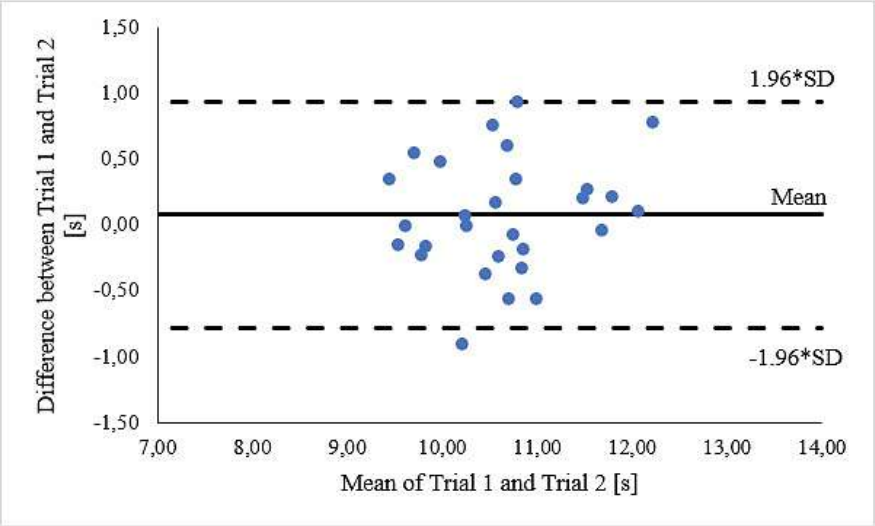

Figure 2. Bland-Altman plot with 95 % CI.

Contributing factors to Triple Y reactive agility performance

Significant moderate to large relationships were found between the Triple Y reactive agility time and times in the 10 m sprint (r = 0.77, p < .001), Go no-go test (r = 0.45, p = .02), and choice reaction test (r = 0.41, p = .03). Initially, all independent variables, including age, body height, body mass, and years of experience, were included in the multiple linear regression model to control for potential confounding effects. However, after assessing significance and multicollinearity, non-significant predictors were removed to achieve a parsimonious model. The final model included performances in choice reaction test, go-no/go test, and 10m sprint test as predictors. The model explained 70 % of the variance in the dependent variable ($F_{(3,24)}$ = 18.70, R^2 = .70, Adjusted R^2 = .66, p < .001). The choice reaction (p = .02) and 10 m sprint (p < .001) were statistically significant predictors, while time in go-no/go test approached significance (p = .07) (Table 3). These findings suggest that performance in the choice reaction and 10 m sprint tests is strongly associated with the outcome variable, even after controlling for other potentially confounding variables.

After adjusting for the explained variance (R^2 = .700), the 10 m sprint test accounted for 37.78 % of the explained variability in 3YRAT performance, followed by choice reaction (17.84 %) and go-no/go test (14.38 %). This indicates that 10 m sprint speed had the strongest influence on the reactive agility test outcome.

Table 3. Multiple regression analysis and predictive model for Triple Y reactive agility test.

Model	**Dependent variable - Triple Y reactive agility test (R = 0.84, R^2 = .70)**					
Predictors	B	β	95 % CI		t	*p*-value
10 m sprint	2.71	0.62	1.59	3.83	4.98	<.001
Go/no-go test	0.06	0.29	0.01	0.11	2.53	.02
Choice reaction test	0.29	0.24	-0.02	0.59	1.94	.07

DISCUSSION

The Triple Y reactive agility test demonstrated good relative reliability (ICC = 0.85). These results are comparable to the intra-session reliability of the Stop-and-Go Reactive Agility Test (SNG-RAT) in college-aged athletes, which ranges from ICC 0.81 to 0.86 (Sekulić et al., 2014). Additionally, a sport-specific reactive

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agility test for basketball players, which used a non-stop movement template, reported reliability values of ICC 0.85 to 0.86 (Sekulić et al., 2017). Pojskić et al. (2018) noted that the intra-session reliability of the SNG-RAT varied across different testing protocols in U17 and U19 soccer players. The second and third protocols showed higher reliability, with ICC values of 0.88 and 0.87, respectively, compared to the first protocol, which had an ICC of 0.70. Their testing sequence included four directional options, similar to the reactive agility test utilized in Sekulić et al. (2014). In contrast, a somewhat lower reliability was found in a football-specific reactive agility test, which involved one directional change followed by a response to one of two options, yielding ICC values of 0.79 in U13 players and 0.82 in U15 players (Krolo et al., 2020). Zeljko et al. (2020) applied the same reactive agility test in futsal players with a mean age of 23 years, reporting ICC values of 0.72 to 0.74. Their testing protocol also incorporated soccer-specific skills, such as kicking the ball. This likely contributed to the slightly lower reliability compared to tests that did not include sport-specific skills. The reliability of the YRAT was also found to be higher than that of the Stop-and-Go Reactive Agility Test involving lateral movements for tennis players, which reported ICC values of 0.72 to 0.74 (Sinković et al., 2022). Overall, the 3YRAT can be considered as reliable as most other validated tests.

The absolute reliability parameters showed acceptable values (SEM % = 2.87, MDC % = 7.96, CV % = 7.43). The value of MDC suggests that any change greater than 0.85 s can be considered a real change beyond measurement error. The SEM is lower than MDC (SEM = 0.31 s) which is desirable. The value of CV is slightly higher than the mean CV for the Y-shaped agility test (approximately 3 %) (Oliver and Meyers, 2009), the reactive agility test for rugby players (2.8 %; Gabbett et al., 2008), and the sport-specific reactive agility test for basketball players (2.9 % to 5 %; Scanlan et al., 2014).

A non-significant difference between the first and second trials indicates that there was no intra-session learning effect. Büchel et al. (2022) demonstrated that a strong learning effect occurs in the reactive agility task from one session to the next. Therefore, inter-session learning should not be entirely disregarded. However, Zemková and Hamar (2001) have found that the learning effect occurred only until the third trial when the protocol with random generating stimuli was used. In 3YRAT, altogether three trials were performed (one practice and two recorded trials). Based on previous observations, including a practice trial is beneficial for minimizing the learning effect in subsequent counting trials, familiarizing participants with the types of stimuli and helping them understand how to coordinate their upper extremity movements to deactivate the sensors. Therefore, two trials after one practice trial may be considered sufficient for evaluating performance in the 3YRAT.

The aim of the study was also to quantify the relationship between measured cognitive and physical variables and the score from a developed reactive agility test (3YRAT), which served as the dependent variable. The time recorded in the 3YRAT significantly correlated with all three variables - 10-meter sprint time ($r = 0.77$, $p < .001$), time in the Go/No-Go test ($r = 0.45$, $p = .02$), and choice reaction time ($r = 0.41$, $p = .03$). This suggests that both motor (38 %) and cognitive components (32 %) significantly contribute to the performance in the 3YRAT. Other studies have also shown a significant correlation between reactive agility performance and sprint speed. This is noted in scenarios involving non-stop running (Horníková and Zemková, 2022; Horníková et al., 2021) as well as the stop-and-go model of the reactive agility test (Chow et al., 2022). However, it is more closely related to the change of direction speed (Krolo et al., 2020; Pojskic et al., 2018; Popowczak et al., 2021). The index of reactivity, which represents the cognitive component, showed a small but significant correlation with stop-and-go reactive agility test performance in professional female basketball and handball players ($r = 0.48$, $p = .007$; Popowczak et al., 2021). In contrast, the correlation was nonsignificant when the reactive Y-shaped agility test was used with soccer players in different playing positions (Fiorilli et al., 2017). This lack of correlation may be due to the simplified context of the Y-shaped

agility test, where a single change of direction followed by a single reaction to a stimulus may not adequately capture the cognitive aspects of reactive agility. The total time in the Y-shaped agility test did not show significant relationships with computer-based simple and choice reaction times (Horníková and Zemková, 2022; Horníková et al., 2021; Matlák et al., 2024). From this viewpoint, using a human stimulus in the Y-shaped agility test was more appropriate when decision time and response movement time were also measured (Henry et al., 2011; Matlák et al., 2024; Young and Willey, 2010). In this study, new setup of cognitive tests assessing visual inhibition and choice reaction were introduced. Although these tests are considered "*laboratory-based*" with general visual stimuli, the results suggest that these tests can sufficiently reflect the cognitive component of the reactive agility performance. The increased demands on perceptual and decision-making compared to previously used reaction time tests, may capture the cognitive aspect of reactive agility more sensitively.

The Y-shaped template is a widely used reactive agility test in team sports. However, stop-and-go tests that require multiple movement responses are gaining popularity (Chow et al., 2022; Pojskić et al., 2018; Popowczak et al., 2021; Sekulić et al., 2014; Krolo et al., 2020). This study may be among the first few to evaluate the reliability of a reactive agility test that combines two scenarios: change of direction with non-stop running (featuring 30° changes of direction before the turns) and a stop-and-go model (including a 180° turn). This design results in a more complex test, because it may be considered both force- and velocity-oriented. Additionally, athletes must respond to three visual stimuli, which is more than what is typically required in the commonly used Y-shaped agility test with non-stop running. Athletes need to cover a longer distance between consecutive movement responses compared to a stop-and-go scenario used by Sekulić et al. (2014), which is closer to the demands of several team sports. As a result, the 3YRAT can be viewed as a compromise between these two approaches, balancing the demands on perceptual-cognitive skills and motor abilities in reactive agility tasks. Although Born et al. (2016) used the reactive agility test which included changes of direction with both scenarios, their test seems to be time-consuming and leads to significant involvement of the glycolytic system compared to our 3YRAT.

It is important to acknowledge certain limitations of this study. Firstly, we are aware of the shortcomings associated with the nature of cross-sectional design and that the experimental study could bring the stronger evidence of practical applicability of 3YRAT. Secondly, the research focuses on only two cognitive tests - neural inhibition and decision-making - which may not fully capture all cognitive abilities related to reactive agility such as pattern recognition, attention, and working memory. Moreover, it is also worth considering shortening the total duration of cognitive tests either by shortening the stimulus generation time or by limiting the maximum response waiting time and adding one or more additional trials. This will avoid the possible occurrence of learning effect, which is a relatively common phenomenon in cognitive tasks. Afterwards, we can avoid the potential occurrence of mental fatigue even in such young athletes. Future research should investigate whether the YRAT can effectively differentiate among athletes from various sports, genders, and performance levels, thereby providing even greater practical and scientific contributions.

CONCLUSIONS

This study proposed a new reliable procedure for assessing reactive agility in youth soccer players and potentially in other athletes involved in "*agility-saturated sports*." This approach provides a more comprehensive diagnostic tool for evaluating agility, because both change of direction scenarios (non-stop running & stop-and-go) are performed. It provides an assessment of the athlete's ability to quickly change running direction at an already acquired speed, as well as decelerate to zero speed and then maximally accelerate again. The Triple Y agility test has been found to be reliable and incorporates essential

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components of agility - cognitive and motor skills. Moreover, cognitive tests used in this study seems to be suitable for detecting the cognitive aspects of reactive agility.

AUTHOR CONTRIBUTIONS

All authors have contributed to all phases of the project. Henrieta Horníková: design of the study, development of the theoretical bases, analysis and interpretation of the data and writing of the article. Filip Skala: study design, data collection, writing the article. The final version of the manuscript was reviewed, edited, and approved by all authors.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Bilateral handgrip deficit is modulated by testing sessions in strength-trained subjects

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ABSTRACT

Background: Although the bilateral deficit (BLD) is a well-documented neuromuscular phenomenon, most studies rely on single-session assessments or strength training interventions, limiting insights into motor learning and task familiarization effects. Objectives: This study aimed to examine the presence of BLD during handgrip contractions across multiple sessions and to assess differences in maximal strength between the dominant and non-dominant hand in unilateral and bilateral conditions, as well as potential sex-related differences. Methods: Thirty-seven resistance-trained participants (19 males, 18 females) performed unilateral and bilateral maximal isometric voluntary contractions (MIVCs) during a handgrip on two separate days. Results: BLD was present in the first session but absent in the second. Sex and handedness dominance did not affect this deficit, but the specific practice of the assessed task did. Conclusions: Our findings indicate that simply performing the grip BLD test significantly modulates bilateral force production. Our findings suggest the need to practice the task being assessed to objectively measure this deficit. This could be relevant from a methodological perspective in the study of this phenomenon.
Keywords: Performance analysis, Bilateral index, Sex-related differences, Dominant hand, Maximal force, Grip strength.

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INTRODUCTION

Bilateral deficit (BLD) is a well-documented neuromuscular phenomenon characterized by a reduction in maximal force output when both limbs are activated simultaneously compared to the sum of the force produced by each limb unilaterally (Henry & Smith, 1961). Due to its relevance in neuromuscular performance, this phenomenon has been extensively examined across different age groups, muscle groups, and movement patterns in both athletic and non-athletic populations within the field of sports science, biomechanics, rehabilitation, and exercise physiology (Jakobi & Chilibeck, 2001; Schantz et al., 1989; Taniguchi, 1998) BLD has been observed across various contraction types, including dynamic (Simoneau-Buessinger et al., 2015), explosive (Rejc et al., 2010), ballistic (Padulo et al., 2022) and isometric contractions (Jakobi & Cafarelli, 1998), with evidence suggesting that isometric contractions tend to elicit more consistent BLD effects than dynamic movements (Jakobi & Cafarelli, 1998). While BLD has been widely studied across different movement patterns, research on its manifestation in the upper limbs remains relatively limited, particularly in isometric handgrip tasks. Previous studies have demonstrated BLD during handgrip contractions, but methodological variations - such as differences in seated versus standing postures - may contribute to discrepancies in findings (Cengiz, 2015; Van Dieen et al., 2003). Additionally, individual characteristics such as sex and handedness have been proposed as potential moderators of BLD. Some studies suggest that males exhibit a greater deficit than females (Ye et al., 2019), while others report no significant sex differences (Carr et al., 2021). Similarly, while some evidence indicates that left-handed individuals experience a smaller BLD (Armstrong & Oldham, 1999), other studies suggest that the role of handedness is complex and context-dependent (Cornwell et al., 2012; Škarabot et al., 2016). Given these inconsistencies, further research is needed to clarify the influence of individual characteristics on BLD, particularly regarding upper limb tasks requiring isometric contractions.

The underlying mechanisms of BLD remain unclear, and several hypotheses suggest that psychological, task-related, physiological, and neurophysiological factors could contribute to this phenomenon (see review in (Škarabot et al., 2016)). A key yet understudied aspect of BLD research is the role of task familiarization and motor learning effects. While most studies have investigated BLD in a single testing session (Magnus & Farthing, 2008) or following long-term strength training interventions (Beurskens et al., 2015; Botton et al., 2016; Janzen et al., 2006), fewer have examined how repeated short-term exposure to bilateral tasks may influence its expression. Carr et al. (2021) observed a progressive decrease in BLD across multiple testing sessions, suggesting a potential role for motor learning effects in modulating bilateral force production. Similarly, Secher et al. (1988) reported reductions in the magnitude of the bilateral deficit in the lower limbs after familiarization in both untrained and trained subjects. However, whether these effects are reproducible in resistance-trained individuals performing maximal isometric contractions in upper limb tasks remains unexplored.

Therefore, the present study aimed to examine the presence and evolution of BLD in the upper limbs of resistance-trained individuals during two sessions of maximal isometric handgrip contractions. Specifically, this study sought to determine whether reduced practice of the task in which the presence of BLD is measured modulates its magnitude and whether this effect differs between the dominant and non-dominant hand in both unilateral and bilateral conditions. Additionally, potential sex-related differences in BLD were explored to assess whether biological factors modulate the response to repeated bilateral task exposure. By addressing these questions, this study provides insight into the extent to which task familiarization contributes to changes in bilateral force production in resistance-trained populations.

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METHODS

Participants

Thirty-seven young and healthy participants (n = 19 males; age = 23.16 ± 1.89 years; stature = 176.32 ± 6.81 cm; body mass = 80.79 ± 19.32 kg; n = 18 females; age = 23.50 ± 2.41 years; stature = 165.44 ± 5.55; body mass = 57.89 ± 8.65 kg) were recruited voluntarily for this study. Inclusion criteria were an age range of 20 to 30 years and a minimum of one year of resistance training experience. Exclusion criteria were the presence of any musculoskeletal injury that could interfere with performance during testing. Participants were also instructed to refrain from any upper-body strength training for 24 hours prior to each assessment session. All participants were provided with a detailed description of the study and written informed consent was obtained prior to testing. This study conformed to the principles of the Declaration of Helsinki of the World Medical Association (1964) and was approved by the Ethics Committee of the Rey Juan Carlos University (no. 0801202000720).

Study design

The study employed a randomized and crossover design conducted over two experimental sessions separated by 7 days, scheduled at the same time of day for each subject (17:00-20:00 h). The same experimental protocol, which involved both unilateral and bilateral maximal isometric voluntary contraction (MIVC), was used in both sessions. Each participant performed isometric strength assessments using a custom handgrip dynamometer. Each session lasted approximately 45 minutes and was conducted in a controlled laboratory environment. Hand dominance was assessed during the first session using the Edinburgh Handedness Inventory (Oldfield, 1971), revealing that all females and 17 male participants were right-handed, while two males were left-handed.

Isometric strength testing sessions

The assessments were carried out with participants standing, arms extended alongside the trunk. The hands were positioned in a neutral grip (i.e., palms facing each other). Prior to the strength testing, participants were familiarized with the handgrip dynamometer and completed a brief warm-up consisting of three isometric contractions of the handgrip muscles at approximately 25, 50 and 75% of their perceived maximum force (Carr et al., 2021). Two minutes after finishing the warm-up, a MIVC accommodation trial was performed under bilateral condition. Later, participants performed three bilateral MIVCs, three unilateral MIVCs with their dominant hand, and three unilateral MIVCs with their non-dominant hand. Each MIVC lasted 5 seconds, with 1 minute of recovery between trials. The strength measurements were identical across sessions but were performed in a randomized order for each participant: (1) maximal unilateral handgrip contraction of the dominant hand, (2) maximal unilateral handgrip contraction of the non-dominant hand, and (3) maximal bilateral handgrip contraction of both hands. Standardized verbal instructions were provided to the participants before each strength trial to motivate for maximal force production ("*squeeze as fast and as hard as you can in 3, 2, 1, go*").

Materials

Data for the unilateral and bilateral maximal isometric voluntary contractions were measured using custom made hand dynamometers using a commercial strain gauge (NL63, 200 kg; Digitimer) with the distance between handles adjusted to each participant (50% of the distance between the middle fingertip to the metacarpophalangeal flexion crease at the base of the thumb). The force signal was amplified (x484) and sampled (2 kHz) for off-line analysis (Power 1401, Cambridge Electronic Design, United Kingdom; sampling frequency 2 kHz).

Data analysis

For all handgrip contractions (unilateral dominant MIVC, unilateral non-dominant MIVC, bilateral dominant MIVC, and bilateral non-dominant MIVC), the average of the maximum force values from the 3 trials was calculated for each participant. The bilateral deficit was then determined using the bilateral index (BI) formula (Howard & Enoka, 1991):

$$BI\ (\%) = \ (100\ x\ (\frac{bilateral}{unilateral\ dominant + unilateral\ \ non - dominant}) \ - \ 100$$

This formula determines the difference between the force produced in a bilateral condition and the sum of the force produced in unilateral conditions, identifying a bilateral deficit when BI < 0.

Statistical analysis

BI were analysed with a two-way mixed ANOVA with one between-subjects factor (sex), and a within-subject factor of session (1 and 2). In addition, bilateral and unilateral MIVCs also were analysed using a four-way mixed ANOVA with one between-subjects factor (Sex), and three within-subjects factors of Hand (dominant and non-dominant), Session (1 and 2) and Condition (unilateral and bilateral). Post-hoc pairwise comparisons were performed using t-tests with Bonferroni corrections. Effect sizes were presented as partial eta squared (ηp^2), with small effect being 0.01-0.06, medium 0.06-0.14, and large ≥ 0.14 (Cohen, 2013). All data are reported as means ± standard deviations. The normality of the differences was checked using the Shapiro–Wilk test and homogeneity of variances was checked using Levene's test. All statistical analyses were conducted using JASP software (version 0.19.3). The alpha level for statistical difference was set at p = .05.

RESULTS

The mean MIVCs data and BI for both sessions are shown in Table 1.

Table 1. Descriptive data (M ± SD) of unilateral and bilateral maximal isometric voluntary contractions and bilateral index for both sessions by sex.

		Male (n = 19) M ± SD		**Female (n = 18) M ± SD**	
		Session 1	Session 2	Session 1	Session 2
Dominant	Unilateral	325.33 ± 65.76	324.77 ± 54.40	217.29 ± 38.06	221.52 ± 33.43
	Bilateral	316.65 ± 64.70	318.30 ± 57.87	206.60 ± 32.45	221.87 ± 39.19
Non-Dominant	Unilateral	289.68 ± 58.48	287.22 ± 59.66	199.94 ± 40.77	193.80 ± 41.12
	Bilateral	287.22 ± 59.66	290.08 ± 59.66	193.80 ± 41.12	203.56 ± 38.03
Bilateral index (%)		- 1.86 ± 3.21	0.65 ± 3.58	- 3.42 ± 6.14	1.04 ± 2.85

Note. M ± SD: Mean ± Standard Deviation. N = Newtons. BI = Bilateral index.

With regard to BI, a two-way mixed ANOVA showed a significant main effect of Session (*F = 12.92, p < .001, ηp^2 = 0.27*), indicating BLD in session 1 (males = - 1.86 ± 3.21; females = - 3.42 ± 6.14) but not in session 2 (males = 0.65 ± 3.58; females = 1.04 ± 2.85) (see Figure 1). However, there was no significant main effect of Sex or interaction between Session × Sex (*p > .05*).

A total of 28 subjects had a BI below 0, and 9 above 0 in the first session. This proportion was practically reversed in the second session, with only 11 subjects having a BI below 0.

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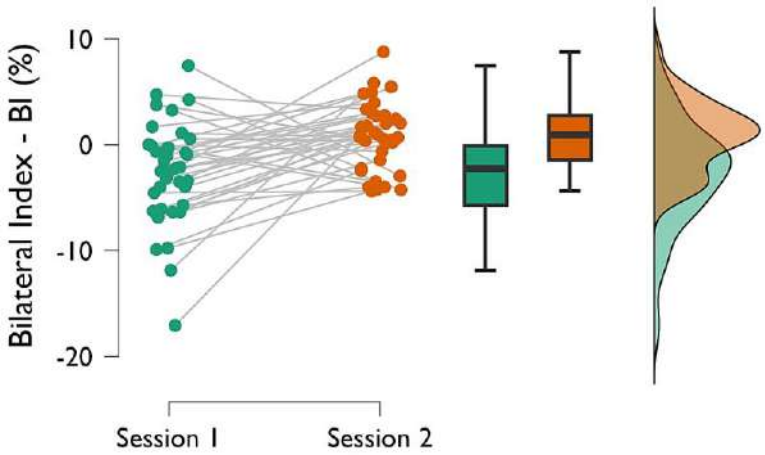
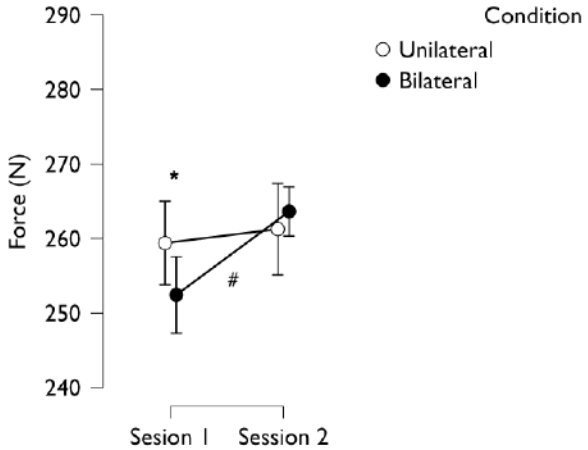


Note. Each dot represents an individual participant, with lines connecting paired values across sessions. Boxplots show the median and interquartile range for each session, and density plots illustrate the distribution of BI values. Negative percentages indicate a bilateral force deficit.

Figure 1. Bilateral index (BI, %) during maximal isometric handgrip contractions in Session 1 and Session 2.

The four-way mixed ANOVA showed significant main effect for Session ($F = 4.38$, $p < .05$, $\eta p^2 = 0.11$), Hand ($F = 71.50$, $p < .001$, $\eta p^2 = 0.67$), and Sex ($F = 38.87$, $p < .001$, $\eta p^2 = 0.53$), whereas no significant effect was found for Condition ($p > .05$). However, these main effects were further qualified by significant interaction effects between Session and Condition ($F = 15.81$, $p < .001$, $\eta p^2 = 0.31$), Hand and Sex ($F = 6.92$, $p < .05$, $\eta p^2 = 0.17$), and Hand and Condition ($F = 8.11$, $p < .05$, $\eta p^2 = 0.19$).

For the Session x Condition interaction, Bonferroni-adjusted post-hoc analyses revealed significant differences between unilateral and bilateral conditions in Session 1 (t = 3.91, d = 0.14, $p < .01$), and between Session 1 and 2 for the bilateral condition only (t = -3.78, d = - 0.23, $p < .01$) (see Figure 2). No other pairwise comparisons reached statistical significance ($p > .05$).

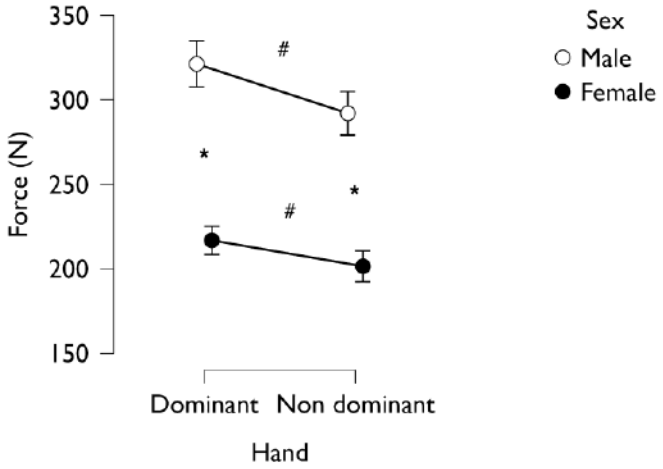


Note. Error bars represent 95% confidence intervals (CI). (*) Indicates statistically significant differences between conditions ($p < .05$). (#) Indicates statistically significant differences between session 1 and session 2 ($p < .05$).

Figure 2. Mean and standard deviation force values in Newtons (N) during unilateral and bilateral conditions in both sessions.

For the Hand x Sex interaction, Bonferroni-adjusted post-hoc analyses showed that dominant hand strength was significantly higher than non-dominant hand strength in both males (t = 7.95, d = 0.59, $p < .001$) and

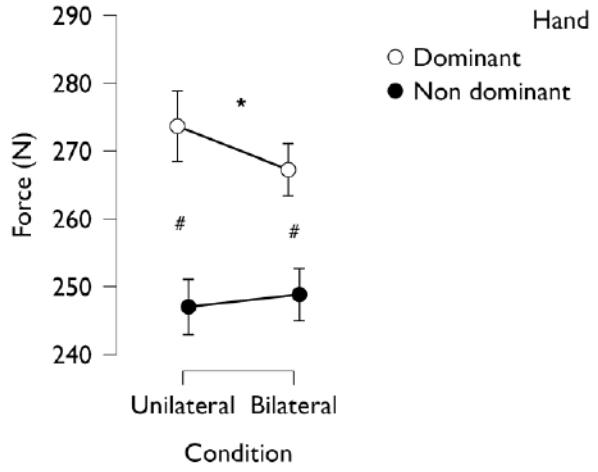
females (t = 4.07, d = 0.31, $p < .01$). In addition, dominant and non-dominant hand strength values in males were significantly higher than in females (t = 6.59, d = 2.09, $p < .001$; t = 5.71, d = 1.82, $p < .001$, respectively). Finally, non-dominant hand strength values for males were significantly higher than dominant hand strength values for females (t = 4.74, d = 1.51, $p < .001$) (see Figure 3).



Note. Error bars represent 95% confidence intervals (CI). (*) Indicates statistically significant differences between males and females (p < .05). (#) Indicates statistically significant differences between dominant and non-dominant hand (p < .05).

Figure 3. Mean and standard deviation values of force in Newtons (N) for males and females in dominant and non-dominant hands.

Regarding the Hand × Condition interaction, Bonferroni-adjusted post hoc analyses revealed that strength values for the dominant hand were significantly higher than those for the non-dominant hand in both unilateral (*t = 7.19, d = 0.53, p < .001*) and bilateral (*t = 8.59, d = 0.37, p < .001*) conditions. In addition, values for dominant hand were also significantly higher in unilateral condition than in bilateral condition (*t = 3.15, d = 0.13, p < .05*), but no significant differences between conditions were observed for non-dominant hand (*p > .05*) (see Figure 4).



Note. Error bars represent 95% confidence intervals (CI). (*) Indicates statistically significant differences between conditions (p < .05). (#) Indicates statistically significant differences between dominant and non-dominant hand (p < .05).

Figure 4. Mean and standard deviation values of force in Newtons (N) in the dominant hand and in the non-dominant hand for unilateral and bilateral conditions.

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DISCUSSION

This study aimed to examine the presence and short-term evolution of the BLD during maximal voluntary isometric handgrip contractions across two separate sessions in resistance-trained individuals. By using a no-intervention repeated measures design, we also sought to determine whether the testing sessions themselves could influence the magnitude of BLD. Additionally, we investigated whether the expression of BLD differed between females and males and assessed strength asymmetries between the dominant and non-dominant hand under both unilateral and bilateral conditions, considering potential sex-related differences. The main finding of this study was the presence of BLD in the first session, indicated by BI values below zero (males = -1.86 ± 3.21; females = -3.42 ± 6.14), and the subsequent absence of this phenomenon in the second session, where BI values rose above zero (males = 0.65 ± 3.58; females = 1.04 ± 2.85).

The BLD during the first session ranged from 1.86 to 3.42%, relative lower than previous studies (Carr et al., 2021; Oda & Moritani, 1995), which BLD was 4.98 and 5.2%, respectively. However, whereas most of those studies assessed handgrip strength in a seated position, the current study used a standing posture. These differences in BLD might initially be thought to be due to the role of posture, a factor that has been shown to affect the presence and size of the BLD. Turnes et al. (2022) observed a more pronounced BLD in the standing versus seated position during a handgrip tasks. In addition, it has been suggested that postural stability plays a critical role in BLD expression, as standing tasks impose greater postural demands that may influence force production and neuromuscular coordination (Pelayo-Tejo et al., 2024). However, according to these studies, we should have found higher BLD values than those reported in the sitting position. Therefore, it is unlikely that these differences are due to posture requirements. Other factors, such as subject characteristics, measuring instruments, or rest duration, could contribute to the different BLD range between studies. It is important to highlight that the participants in our study were resistance-trained individuals familiar with both unilateral and bilateral exercises, although not with the task being tested. The presence of BLD during the first session suggests that general training experience is not enough to abolish this phenomenon.

The absence of BLD in the second session indicates that short-term task practice can significantly modulate bilateral force production. This result aligns with prior findings indicating that short-term exposure to a specific motor task could improve force coordination and neuromuscular efficiency (Secher et al., 1988). In addition, the role of cognitive engagement should not be overlooked, as motor learning through repetition has been shown to optimize force distribution in bilateral tasks (Farthing et al., 2009). Therefore, it is worth considering whether bilateral grip strength deficit is a relevant phenomenon from a training and rehabilitation perspective or, on the contrary, a futile phenomenon resulting from insufficient practice in the task being assessed. In any case, methodologically, this study highlights the importance of conducting at least two sessions of bilateral grip deficit assessment to explore the presence or absence of this phenomenon.

Sex-related differences in BLD were not observed, consistent with previous research suggesting that both males and females experience similar BLD during handgrip contractions (Carr et al., 2021). As expected, males exhibited greater absolute force output than females in both unilateral and bilateral conditions, in line with established sex differences in upper limb strength (Ye et al., 2019). In our study the hand dominance was not a factor affecting the BLD, with greater strength in the dominant than in non-dominant hand independent of whether the contraction was performed unilaterally or bilaterally. The greater strength demonstrated by the dominant hand is in line with a recent meta-analysis of 87 scientific studies (Foley et al., 2025). The effect of hand dominance on bilateral deficits is inconclusive. Initially, it was suggested that the bilateral deficit is due to force reduction in the dominant limb (Henry & Smith, 1961). However, the only study that assessed bilateral deficits, considering handedness and laterality, only observed bilateral deficits

in the left-handed group (Cornwell et al., 2012). Our study does not support these results, given that our sample consisted of right-handed individuals, except for two subjects. Further studies, including laterality and handedness, are needed to evaluate their role in bilateral deficits.

This study has several limitations. First, we only measured bilateral grip deficits. We selected this action based on Simoneau-Buessinger et al. (2015), who proposed that handgrip exercises minimize the influence of postural stability, providing a more isolated model for assessing bilateral force production mechanisms. Therefore, we do not know whether our results can be extrapolated to other types of contractions involving different muscle groups. Second, we only explored bilateral grip deficits in two sessions, so we lack data to evaluate the effect of practice across multiple testing sessions.

CONCLUSIONS

In conclusion, our study with strength-trained subjects indicates the presence of a bilateral grip deficit in the first assessment session but not in the second. Sex and handedness dominance did not affect this deficit, but the specific practice of the assessed task did. Our results suggest the need to practice the task being assessed to objectively measure this deficit. This could be relevant from a methodological perspective in the study of this phenomenon.

AUTHOR CONTRIBUTIONS

Conceptualization: Miguel Fernández-del-Olmo, Antonio Luque-Casado. Methodology: Miguel Fernández-del-Olmo. Data collection: Elvira Molinero-Martín, Víctor López-Zarraute. Data curation and formal analysis: Elvira Molinero-Martín, Miguel Fernández-del-Olmo. Writing–original draft: Elvira Molinero-Martín, Víctor López-Zarraute, Antonio Luque-Casado. Writing–review & editing: Elvira Molinero-Martín, Miguel Fernández-del-Olmo, Antonio Luque-Casado, Víctor López-Zarraute. Project administration: Miguel Fernández-del-Olmo, Antonio Luque-Casado.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Small-sided games (ssg) internal and external load on different pitch sizes in young elite women football players

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ABSTRACT

The present study aimed to assess and compare the internal and external training loads experienced by elite young female football players during small-sided games (SSGs) conducted on two different pitch sizes. Eight athletes (age: 19.6 ± 3.7 years) from a top-tier Greek women's football team participated in two training sessions and one official match. GPS tracking and heart rate monitoring were used to collect data on total distance, speed zones, sprint count, maximum speed, and heart rate distribution across five intensity zones. Two SSG formats (4v4) were implemented: one on a 20×30 m pitch (75 m²/player) and one on a 30×40 m pitch (150 m²/player), each consisting of four 4-minute bouts with 2-minute passive recovery. The results revealed no significant differences in internal load (heart rate responses) between the two pitch sizes. However, external load metrics varied notably: the smaller pitch induced more frequent accelerations and decelerations ($p < .05$), while the larger pitch resulted in longer total distances and more sprints ($p < .05$). These findings highlight the influence of pitch size on movement demands, with smaller areas favouring anaerobic, change-of-direction actions and larger areas promoting mostly aerobic and high-speed activities. The study emphasizes the effectiveness of SSGs in conditioning programs and supports their role in developing both aerobic and anaerobic fitness within realistic game contexts. The application of GPS technology enabled precise workload quantification, offering valuable insights for individualized training design. Importantly, this research addresses a gap in the literature regarding elite young women footballers, providing practical guidance for coaches aiming to optimize performance and minimize injury risk through targeted SSG configurations.

Keywords: Performance analysis, GPS tracking, Small-Sided Games (SSG), Young women's football.

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INTRODUCTION

The aggressive development of technology is allowing the football community to better analyse training and thus make it more effective. At the top level, attention to detail, in addition to the planning and execution of training sessions, is what sets teams apart and makes them stand out. The use of GPS devices (Global Position System) is of great concern to the technical staff of the teams to monitor the players' performance during either training or a match. In this way, people are well trained in the use of these devices, draw useful information about the physiological demands of the training or one of its parts, and later inform the coaches.

More specifically, at the high level and mainly in men footballers many studies refer to the recording of data from GPS devices to monitor the training load received by the players through the training units (and more often reference is made to the components of these competitive games) and the competitions involved (Gómez-Carmona et al., 2018). The GPS devices give useful information about heart rate, speed, total distance, as well as their changes during the tracking time. This information allows for improving the quality of training and makes it easier for the coaches to achieve their goals for each training session by regulating the intensity and the load of every training. However, researchers are paying attention to acceleration and deceleration to reach useful conclusions about the player's performance (Hodgson et al., 2013). These devices give a lot of data to analyse and draw important results.

An important chapter of football is injuries. Many researchers have started working on how GPS monitoring can help teams to prevent injuries. A lot of them mention that it is worth paying attention to players' internal loads over time to prevent injuries (Ehrmann et al., 2016; Ravé et al., 2020), but the variables of these devices are also useful for controlling the player's return to train or to play (Franchini et al., 2018). Common studies about youth leagues refer to the relationship between the training load and injury prevention. After a systematic review of research using GPS tracking during the training sessions and the official games at youth academies, the researchers concluded that, from continuous monitoring of training load, there is a possibility to prevent injuries and also control their fitness level (Ravé et al., 2020). Nowadays, reality-based learning concerns most coaches to build the training protocol. So, for this reason, coaches are trying to simulate players with training exercises similar to the real game. Researchers have found that SSGs (Small-Sided Games) with different pitch sizes could be used for this kind of training (Hill-Haas et al., 2011). Based on this idea some researchers tried to track and match the player's load during official or not championship games and training sessions (Casamichana et al., 2012). These game formats are easy to fix and fit into the training goal and this is the reason they are usually used. Coaches can easily plan to improve the fitness level of the player's performance as SSG can, as generally agreed, help increase the aerobic and anaerobic levels. It is important to mention that the rules coaches could set are the facts which are controlling the purpose of those games during the training (Aguiar et al., 2013).

Most researchers are working on men's football development. The knowledge about women's football is poor, especially about the SSGs and GPS tracking. However, there is some research which is referring to physical responses during the training sessions. (Mara et al., 2016). From this research, there are no significant differences between men's and women's physical responses during the SSGs but it's clear for both men and women that these games can improve their aerobic-anaerobic levels (Mara et al., 2016). FIFA is trying to improve the football game for women with a lot of projects and activities. This movement to be successful must be supported by appropriate knowledge. There are many investigations of women's football teams in Europe, but there are very few in Greece. To diminish this disadvantage, this article investigates the variables from GPS in the champion team of the 1st League of Women's Football in Greece.

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This research highlights the integration of technology, specifically GPS tracking systems, in analysing Small-Sided Games (SSGs) and their impact on young female football players. The use of advanced tracking technology provides detailed insights into the physiological demands of training, enabling coaches to refine their methods for improved performance and injury prevention. Given the limited research on SSGs in women's football, especially among young athletes, this study aims to bridge the gap by offering data-driven insights that can help optimize training strategies and contribute to the sport's overall development.

MATERIAL AND METHODS

Participants

The experiment involved eight (8) players who participated throughout the official competitive match, with an average age of 19.6 ± 3.7 years, height of 162.2 ± 4.5 cm, body weight of 57.4 ± 4 kg, and body fat percentage of 19.06 ± 2.1%. All the athletes participated in six (6) training sessions and one match during the study. The match, which took place during the experimental phase, was part of the top division of the Greek women's football league, and data was recorded from the same team and the same players. All testing procedures were explained to participants before the start of the study, and they all participated voluntarily. Written informed consent was signed by all participants before any testing procedure. The study was approved by our university's Institutional Review Board (approval number EH 28/2020) and was conducted according to the Declaration of Helsinki.

Measures

For the execution of the experiment and based on existing literature (Hill-Haas et al., 2011), two different dimensions of the competitive playing area were selected. The measurements were made on separate days for each selected playing space. The recordings were conducted at the same time of day and at the same time during the training session and on the same day in two consecutive weeks. The training parameters were recorded using the Global Positioning System (GPS) from POLAR. The selection of players was based on their positions on the field. Specifically, two wide defenders, two defensive midfielders, two attacking midfielders, and two wide attackers were selected. Furthermore, the teams were divided based on player positions to form a 4v4 setup. For each team, one defender, two midfielders, and one attacker were chosen. This team distribution followed existing literature to establish a correlation between the playing areas and match conditions (one player from each line). The GPS devices were placed on the eight players, using bands, before the warm-up. The athletes participated normally in the team's warm-up session and, once physically ready, took part in the competitive games prepared during the warm-up period.

GPS variables

Using the POLAR devices, the necessary variables were recorded. The total distance (in meters), maximum heart rate, and game time in the five different heart rate zones were recorded. (Zone 1 = 50%-59%, Zone 2 = 60%-69%, Zone 3 = 70%-79%, Zone 4 = 80%-89%, and Zone 5 = 90%-100%). Additionally, the distance each player ran about her speed was categorized into five zones, the total number of sprints (with speeds above 19 km/h), and the maximum speed reached by each player. (Zone 1 = 3-6.99 km/h, Zone 2 = 7-10.99 km/h, Zone 3 = 11-14.99 km/h, Zone 4 = 15-18.99 km/h, Zone 5 = 19+ km/h).

Competitive games

According to existing literature, the first competitive game took place in a 20x30 meter space, with a total area of 600 square meters and a player-to-area ratio of 75 square meters per player. The second game took place one week later in a 30x40 meter space, totalling 1200 square meters, with a player-to-area ratio of 150 square meters per player. The duration of each game was four (4) minutes with four (4) repetitions and a two

(2) minute recovery time between them. The total duration of the experiment, including breaks, was twenty-two (22) minutes. During the games, efforts were made to maintain the rhythm. To achieve this, balls were placed in the corners of the square, and whenever the ball was lost, the trainer kicked one of the outside balls inside the playing area immediately. There were no restrictions in the game rules regarding passing or the number of ball touches. This allowed the players to play free football, simulating more realistic match conditions. After the completion of the competitive square process, the GPS devices were removed from the players before the end of their overall training session. After the final four-minute period, the players followed the coach's training plan, which involved a full-field competitive game.

Procedures

The purpose of the study is to record and compare the training parameters of competitive games during the training session in spaces of different dimensions. The recordings were made at a sports centre for football in Thessaloniki, Greece. The experiment was completed over a span of seven days, with data being recorded during two team training sessions, one week apart.

Analysis

Designed for statistical analyses, descriptive statistics were initially used to summarize the anthropometric characteristics, highlighting the mean, standard deviation, minimum, and maximum values. Additionally, the test of normality to assess whether our variables followed a normal distribution was conducted. Specifically, the researchers applied the Shapiro-Wilk test due to the sample size, using a significance level of $p < .05$. For variables that followed a normal distribution, an independent samples t-test to examine mean differences between the number of attempts and the variables under investigation was employed. For variables that did not follow a normal distribution, the researchers used the non-parametric Kruskal-Wallis test.

RESULTS

The sample consisted of eight (8) players from the team, those who played most of the championship games. Tables 1 and 2 present the anthropometric and physiological characteristics of the players.

Table 1. Anthropometric characteristics of players.

	N	Minimum	Maximum	Mean ± Std. Deviation
Height (cm)*	8	157.00	169.00	162.12 ± 4.54
Weight (kg)*	8	52.00	63.70	57.42 ± 4.02
Age (y)*	8	16.00	27.00	19.62 ± 3.70
Body fat (%)*	8	16.20	23.11	19.06 ± 2.13
Valid N (listwise)	8			

*Note. *A normality test of the value distribution was conducted using the Shapiro-Wilk test.*

Table 2. Physiological characteristics of players.

	Group (Number of attempts)	N	Mean ± Std. Deviation	Std. Error Mean
HR/min [bpm]	1.00	8	109.37 ± 8.89	3.14
	2.00	8	107.00 ± 12.88	4.55
HR avg/min [bpm]	1.00	8	159.87 ± 4.67	1.65
	2.00	8	162.00 ± 8.07	2.85
HR max/min [bpm]	1.00	8	183.00 ± 7.87	2.78
	2.00	8	183.62 ± 8.21	2.90
HR [%]	1.00	8	55.25 ± 4.49	1.58
	2.00	8	54.12 ± 6.42	2.27

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HR avg [%]	1.00	8	81.00 ± 2.50	0.88
	2.00	8	81.62 ± 4.10	1.45
HR max [%]	1.00	8	92.50 ± 4.95	1.75
	2.00	8	92.62 ± 4.10	1.45
Time in HR zone 1 (50 - 59 %)	1.00	8	0.77 ± 0.86	0.30
	2.00	8	1.04 ± 0.97	0.34
Time in HR zone 2 (60 - 69 %)	1.00	8	3.23 ± 0.44	0.15
	2.00	8	2.94 ± 0.72	0.25
Time in HR zone 3 (70 - 79 %)	1.00	8	3.01 ± 1.37	0.48
	2.00	8	2.50 ± 0.80	0.28
Time in HR zone 4 (80 - 89 %)	1.00	8	10.80±2.32	0.82
	2.00	8	9.29±4.87	1.72
Time in HR zone 5 (90 - 100 %)	1.00	8	3.84±3.41	1.20
	2.00	8	6.16±5.87	2.07

According to the test results, all variables show normal distribution (p > .05) except for the variables: a) maximum HR (%), b) time in zone HR 2, c) time in HR zone 3, d) time in HR zone 5 (p < .05) e) distance in speed zone 4, f) time in power zone 2 (p < .05) (Table 3).

Table 3. Tests of Normality.

Variable	Shapiro-Wilk Statistic	df	Sig
Height	.902	7	.343
Weight	.923	7	.492
Age	.867	7	.175
Fat	.915	7	.433
HR at Rest [bpm]	.914	7	.427
Mean HR [bpm]	.891	7	.280
Max HR [bpm]	.940	7	.636
HR [%]	.966	7	.864
Mean HR [%]	.852	7	.127
Max HR [%]	.871	7	.189
Time in HR Zone 1 (50 - 59%)	.870	7	.184
Time in HR Zone 2 (60 - 69%)	.690	7	**.003**
Time in HR Zone 3 (70 - 79%)	.738	7	**.010**
Time in HR Zone 4 (80 - 89%)	.924	7	.499
Time in HR Zone 5 (90 - 100%)	.799	7	**.040**
Total Distance [m]	.964	7	.849
Distance/Minute [m/min]	.960	7	.817
Max Speed [km/h]	.967	7	.879
Mean Speed [km/h]	.959	7	.810
Sprints	.835	7	.089
Distance in Speed Zone 1 (3.00 - 6.99 km/h)	.933	7	.581
Distance in Speed Zone 2 (7.00 - 10.99 km/h)	.931	7	.563
Distance in Speed Zone 3 (11.00 - 14.99 km/h)	.906	7	.371
Distance in Speed Zone 4 (15.00 - 18.99 km/h)	.798	7	**.039**
Distance in Speed Zone 5 (19.00+ km/h)	.888	7	.266
Training Load Score	.956	7	.782
Cardio Load	.991	7	.994
Recovery Time [h]	.971	7	.902
Calories [kcal]	.914	7	.426
Number of Decelerations (-50.00 to -3.00 m/s²)	.979	7	.956

Number of Decelerations (-2.99 to -2.00 m/s²)	.947	7	.704
Number of Decelerations (-1.99 to -1.00 m/s²)	.882	7	.236
Number of Decelerations (-0.99 to -0.50 m/s²)	.915	7	.432
Number of Accelerations (0.50 to 0.99 m/s²)	.868	7	.178
Number of Accelerations (1.00 to 1.99 m/s²)	.937	7	.610
Number of Accelerations (2.00 to 2.99 m/s²)	.849	7	.120
Number of Accelerations (3.00 to 50.00 m/s²)	.912	7	.409
Time in Power Zone 1 (70 - 84%)	.973	7	.919
Time in Power Zone 2 (85 - 99%)	.661	7	**.001**
Time in Power Zone 3 (100 - 129%)	.831	7	.082
Time in Power Zone 4 (130 - 179%)	.845	7	.112
Time in Power Zone 5 (180 - 800%)	.984	7	.978
Muscle Load in Zone 1 (70 - 84%)	.920	7	.471
Muscle Load in Zone 2 (85 - 99%)	.825	7	.071
Muscle Load in Zone 3 (100 - 129%)	.990	7	.994
Muscle Load in Zone 4 (130 - 179%)	.944	7	.679
Muscle Load in Zone 5 (180 - 800%)	.926	7	.521
Total Muscle Load	.923	7	.492

T-test results for independent samples

A T-test for independent samples was performed for the variables that followed the normal distribution. The results showed statistically significant differences between the two conditions of SSGs ($p < .05$). Specifically, there was a statistically significant difference between the two different conditions of SSGs and total distance with $t(14) = -5.546$, $p < .001$, MD = -347. Moreover, statistically significant differences were observed between the two different conditions of SSGs and distance with $t(14) = -5.228$, $p < .001$, MD = -14.5. Statistically significant differences were also shown between the two different conditions of SSGs and max speed with $t(14) = -2.629$, $p < .05$, MD = -2.43. Furthermore, statistically significant differences were observed between the two different conditions of SSGs and average speed with $t(14) = -4.870$, $p < .001$, MD = -.86. Statistically significant differences were also shown between the two different conditions of SSGs and distance in speed zone 2 with $t(14) = -2.771$, $p < .05$, MD = -111.13. Statistically significant differences were also shown between the two different conditions of SSGs and distance in speed zones 3, 4, and 5 with $t(14) = -4.418$, $p < .01$, MD = -204.88, $t(14) = -5.884$, $p < .001$, MD = -103.63 and $t(7.9) = -3.299$, $p < .05$, MD = -17, respectively. Statistically significant differences were also shown between the two different conditions of SSGs and time in power zone 1, 3, 4, 5 with $t(14) = -2.804$, $p < .05$, MD = .31, $t(14) = -2.553$, $p < .05$, MD = -45, $t(9.5) = -3.249$, $p < .01$, MD = -.47 and $t(8.5) = -2.466$, $p < .05$, MD = -.32, respectively. Finally, statistically significant differences were shown between the two different conditions of SSGs and muscle load in power zone 1, 2, 3, 4, 5 and muscle load, with $t(14) = -4.615$, $p < .001$, MD = -4.25, $t(14) = -3.809$, $p < .01$, MD = -4, $t(14) = -3.706$, $p < .01$, MD = -7, $t(14) = -3.848$, $p < .01$, MD = -8.63, $t(14) = -2.741$, $p < .05$, MD = -10.63 and $t(14) = -5.600$, $p < .001$, MD = -32.38, respectively. This information is shown in Table 4.

For the variables that showed non-normal distribution, the Kruskal-Wallis Test was performed. The results showed statistically significant differences between the number of attempts and distance in speed zone 4 (metres), with $H(1) = 11.294$, $p < .001$. Moreover, there was also a statistically significant difference between the number of attempts and time in power zone 2, with $H(1) = 7.225$, $p < .01$. There was not a statistically significant difference for time in HR zone 2, time in HR zone 3, and time in HR zone 5. This information is represented in Table 5.

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Table 4. T-test for independent samples.

		Levene's Test for Equality of Variances		t-test for Equality of Means				
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
Total distance [m]	Equal variances assumed	0.016	.901	-5.546	14	.000	-347.000	62.56425
	Equal variances not assumed			-5.546	13.261	.000	-347.000	62.56425
Distance/min [m/min]	Equal variances assumed	0.004	.949	-5.228	14	.000	-14.5000	2.77344
	Equal variances not assumed			-5.228	13.427	.000	-14.5000	2.77344
Max speed [km/h]	Equal variances assumed	0.701	.417	-2.629	14	.020	-2.42500	.92241
	Equal variances not assumed			-2.629	13.187	.021	-2.42500	.92241
Avg speed [km/h]	Equal variances assumed	0.033	.858	-4.870	14	.000	-.87500	.17966
	Equal variances not assumed			-4.870	13.600	.000	-.87500	.17966
Distance in speed zone 2 [metres] (7.00 - 10.99 km/h)	Equal variances assumed	4.130	.062	-2.771	14	.015	-111.12500	40.10797
	Equal variances not assumed			-2.771	10.268	.019	-111.12500	40.10797
Distance in speed zone 3 [metres] (11.00 - 14.99 km/h)	Equal variances assumed	0.102	.754	-4.418	14	.001	-204.87500	46.36816
	Equal variances not assumed			-4.418	12.863	.001	-204.87500	46.36816
Distance in speed zone 4 [metres] (15.00 - 18.99 km/h)	Equal variances assumed	0.665	.429	-5.884	14	.000	-103.62500	17.61258
	Equal variances not assumed			-5.884	11.713	.000	-103.62500	17.61258
Distance in speed zone 5 [metres] (19.00- km/h)	Equal variances assumed	14.500	.002	-3.299	14	.005	-17.00000	5.15302
	Equal variances not assumed			-3.299	7.893	.011	-17.00000	5.15302
Time in power zone 1 (70 - 84 %)	Equal variances assumed	3.016	.104	-2.804	14	.014	-.30875	.11012
	Equal variances not assumed			-2.804	10.770	.017	-.30875	.11012
Time in power zone 3 (100 - 129 %)	Equal variances assumed	2.816	.115	-2.553	14	.023	-.44500	.17432
	Equal variances not assumed			-2.553	13.030	.024	-.44500	.17432
Time in power zone 4 (130 - 179 %)	Equal variances assumed	32.394	.000	-3.249	14	.006	-.47000	.14467
	Equal variances not assumed			-3.249	9.467	.009	-.47000	.14467
Time in power zone 5 (180 - 800 %)	Equal variances assumed	8.392	.012	-2.466	14	.027	-.32375	.13128
	Equal variances not assumed			-2.466	8.503	.037	-.32375	.13128
Muscle load in power zone 1 (70 - 84 %)	Equal variances assumed	0.206	.657	-4.615	14	.000	-4.25000	.92099
	Equal variances not assumed			-4.615	13.659	.000	-4.25000	.92099
Muscle load in power zone 2 (85 - 99 %)	Equal variances assumed	0.000	1.000	-3.809	14	.002	-4.00000	1.05009
	Equal variances not assumed			-3.809	13.869	.002	-4.00000	1.05009
Muscle load in power zone 3 (100 - 129 %)	Equal variances assumed	0.148	.706	-3.706	14	.002	-7.00000	1.88864
	Equal variances not assumed			-3.706	13.650	.002	-7.00000	1.88864
Muscle load in power zone 4 (130 - 179 %)	Equal variances assumed	1.242	.284	-3.848	14	.002	-8.62500	2.24155
	Equal variances not assumed			-3.848	12.691	.002	-8.62500	2.24155
Muscle load in power zone 5 (180 - 800 %)	Equal variances assumed	2.365	.146	-2.741	14	.016	-10.62500	3.87615
	Equal variances not assumed			-2.741	11.352	.019	-10.62500	3.87615
Muscle load	Equal variances assumed	0.550	.471	-5.600	14	.000	-32.37500	5.78078
	Equal variances not assumed			-5.600	12.617	.000	-32.37500	5.78078

Table 5. Kruskal Wallis Test for independent samples [a,b].

	Distance in speed zone 4 [metres] (15.00 - 18.99 km/h)	**Time in power zone 2 (85 - 99 %)**
Kruskal-Wallis H	11.294	7.225
df	1	1
Asymp. Sig.	<.001	.007

Note. a. Kruskal Wallis Test. b. Grouping Variable: number of attempts.

DISCUSSION

The present study revealed significant differences between the two SSG conditions across a range of performance and physiological variables. Independent samples t-tests indicated that players covered significantly less total distance and distance under one condition compared to the other. Additionally, significant reductions were observed in maximum and average speed. Distances covered in speed zones 2, 3, 4, and 5 were also significantly lower, indicating a general decline in high-intensity activity. Significant differences were further noted in time spent in power zones 1, 3, 4, and 5, suggesting changes in the physical demands associated with each condition. Muscle load also varied significantly between conditions across all five power zones, with notable reductions in total muscle load. The Kruskal-Wallis test also identified significant effects of the number of attempts on distance covered in speed zone 4 and time in power zone 2, while no significant differences were found for time spent in HR zones 2, 3, and 5. These findings highlight that different SSG configurations can lead to markedly different physical and physiological demands, with implications for training load management and session design in team sports.

The findings of this study provide valuable insights into the physiological demands and performance variations of elite female football players under different Small-Sided Games (SSG) conditions. The results indicate that there were no statistically significant differences in heart rate indicators between the two pitch sizes, suggesting that the intensity level remained relatively stable. However, the variations in total distance covered, acceleration, and deceleration patterns highlight the impact of pitch size on external load variables.

In line with previous research (Mara et al., 2016). The data confirm that smaller playing areas (20x30m) demand more frequent changes in direction and explosive movements, leading to increased accelerations and decelerations. This aligns with the notion that reduced space promotes higher intensity through shorter but more frequent high-intensity actions. Conversely, the larger pitch (30x40m) resulted in a higher number of sprints and greater total distance covered, which may be attributed to the increased space available for movement and the necessity to cover larger distances to maintain positional structure. These findings reinforce the importance of pitch size selection in training design, depending on the desired physical outcomes (Köklü eta al., 2013; Nunes et al., 2021).

The use of GPS tracking technology in this study has provided precise and quantifiable data on player workload, allowing for a more comprehensive analysis of training intensity. The ability to monitor internal (heart rate zones) and external (distance, speed, and acceleration) loads enables coaches to optimize training sessions by balancing workload and recovery. Importantly, the findings contribute to the limited body of knowledge on GPS applications in elite women's football, where research remains significantly less developed compared to men's football (Mara et al., 2016; Scott et al., 2020; Castellano et al., 2013; Halouani et al., 2014).

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Another critical aspect highlighted by this study is the role of SSGs in conditioning programs. The findings confirm that SSGs serve as an effective training method for improving both aerobic and anaerobic fitness while maintaining game-specific movement patterns. The ability to simulate match intensity while manipulating pitch dimensions offers coaches a valuable tool for player development. Furthermore, as FIFA and other organizations strive to enhance the competitive level of women's football, research-based training methods such as those investigated here will be crucial for improving player performance and reducing injury risks (Hill-Haas et al., 2011; Aguiar et al., 2013; Castellano et al., 2013).

One of the key contributions of this study is its focus on elite young female players, a demographic often underrepresented in sports science research. From a motor development perspective, training young athletes using structured SSGs and GPS monitoring allows for optimal neuromuscular adaptation, coordination enhancement, and progressive workload management (Beenham et al., 2017). This not only improves performance but also contributes to long-term athletic development, reducing the risk of overuse injuries and ensuring sustained growth in the sport (Ehrmann et al., 2016; Ravé et al., 2020). By analysing the training load of top-level female athletes, this study helps bridge the knowledge gap and offers practical insights for clubs and national teams looking to optimize training regimens for female players. Given that most existing studies focus on men's football, these findings provide a necessary foundation for developing sex-specific training recommendations (Martínez-Lagunas et al., 2014; Strauss et al., 2019; López-Fernández et al., 2017).

Future research should further explore the interaction between different SSG formats and player performance, incorporating additional metrics such as muscle oxygenation and neuromuscular fatigue. Video-based motion analysis could complement GPS data to provide deeper insights into technical and tactical adaptations during SSGs. Additionally, expanding the sample size and including players from different competitive levels would enhance the generalizability of these findings.

CONCLUSIONS

In conclusion, this study reinforces the value of GPS technology in assessing training demands and highlights the significance of pitch size in structuring SSGs. Focusing on elite young female players, it contributes to the growing body of research aimed at improving women's football through data-driven training methodologies. These insights can be directly applied to coaching strategies, helping to enhance player development, optimize performance, and reduce injury risks in elite young women's football.

AUTHOR CONTRIBUTIONS

All authors contributed significantly to the final version of this manuscript and to the interpretation of the results. P. C.: literature review, data collection, and manuscript writing, E. S.: conceptualization, study design, statistical analysis support, supervision, as well as assisted in manuscript preparation, A.L.: contributed to methodology design, data interpretation, and critical revision of the manuscript, as well as assisted in manuscript preparation, G. S.: statistical analysis support, data organization, data analysis, and drafting of specific sections, I. T.: technical support, data processing, and contribution to the discussion and conclusions. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors. The experiments comply with the current laws of the country in which they were performed.

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ORIGINAL ARTICLE

Are there differences in maximal isometric force and rapid force characteristics in Division II American collegiate football players?

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ABSTRACT

The aim of this study was to see if maximal isometric force characteristics could discriminate positional groupings in division II American college football players. Methods: Thirty-eight male collegiate athletes (mean ± SD: age 20.37 ± 1.62 years, height 185.37 ± 5.04 cm, and weight 101.89 ± 20.13 kg) performed maximal isometric mid-thigh pulls. Peak force, time-specific force, and rate of force development was calculated from a force-time curve. A one-way ANOVA with Bonferroni post-hoc adjustments was used to examine position differences between Line (n = 16), Large Skill (n = 9), and Small Skill (n = 13) position groups with α priori set at $p < .05$. Results: There was a significant difference for peak force, where OD/L and LS had greater PF compared to SS ($p \leq .001 – .026$), additionally, OD/L had greater PF than LS ($p = .022$). Time-specific force-time curve forces (PF50ms–PF250ms) reported greater forces for OD/L and LS compared to SS ($p \leq .001 – .036$), and PF150 was greater for OD/L compared to LS ($p = .047$). For RFD, LS had greater RFD compared to SS and OD/L for RFD 0-50ms ($p = .005 – .020$). Conclusion: These findings suggest the importance of assessing time-specific forces, and RFD phases from isometric force-time curves with American football players. Coaches and strength staff may refer to these findings when designing conditioning programs for collegiate football players.

Keywords: Performance analysis, Rapid strength, Rapid force, Force-Time curve.

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INTRODUCTION

Athletic performance can vary depending on sport, however, for American football athletes, a multitude of abilities are required for success (Black & Roundy, 1994; Burke et al., 1980; Fry & Kraemer, 1991; Fry et al., 1991; Secora et al., 2004). For example, it is suggested that American football players should strength train and condition their bodies to be able to achieve optimal aerobic fitness, muscular endurance, upper and lower body muscular strength and power, maximal sprinting and agility performance (Black & Roundy, 1994; Fry & Kraemer, 1991; Garstecki et al., 2004; Mann et al., 2016). While possessing said characteristics for athletic performance are important, when using force plates, Merrigan et al., (2022) reported specific countermovement jump outcomes between different positions on the team. Specifically, skill and hybrid players reported greater jump height, braking and propulsive forces/power, and modified reactive strength index compared to other positions. Further, lineman created the greatest absolute forces but were slower (time wise) during jumping attempts. Although dynamic training can be beneficial for athletes (bench press, squat, power clean, sprint and agility training), the ability to assess isometric strength (dynamometer, load cell, force plates) can provide both reliable and in-depth analyses (Christ et al., 1994; Comfort et al., 2019; Thompson, Ryan, Sobolewski, Smith, Conchola, et al., 2013). Specifically, analysis of an isometric force-time curve (time-specific and rate of force development across a phase of time) enables researchers the ability to assess a multitude of variables that are important, i.e., maximum force, rate of force development, early and late RFD (Aagaard et al., 2002; Andersen & Aagaard, 2006; Andersen et al., 2010). For example, it typically takes (>300 milliseconds) to achieve maximal strength when performing an isometric contraction (Aagaard et al., 2002; Andersen et al., 2010), however, early rapid force/strength (<100 ms) and late force/strength (>200 ms) can directly tie back to muscle fibre type, and neural properties (Andersen & Aagaard, 2006).

While a handful of studies have assessed American football players on isometric strength (Johnson et al., 2025; McGuigan & Winchester, 2008; Thompson, Ryan, Sobolewski, Smith, Conchola, et al., 2013), previous literature either assessed starters (Johnson et al., 2025), starters vs. non-starters (Thompson, Ryan, Sobolewski, Smith, Conchola, et al., 2013), or attempted to see if weight room strength and the IMTP correlated (McGuigan & Winchester, 2008). Additionally, while able to differentiate athletic status (starter vs. non-starter), Thompson et al. (2013) assessed quadriceps and hamstrings (individually), using an isokinetic dynamometer. While their findings are unique (hamstring early RFD was greater for starters compared to non-starters), assessing athletes from a multi-joint position (isometric mid-thigh pull), can depict greater specificity to sport, rather than maximum voluntary isometric contractions from an isokinetic dynamometer. Further, using force plates enables researchers the ability to perform field-based tests rather than lab-based testing, potentially allowing for greater participation rates within the team, and faster data collection sessions. Based on limited research investigating maximal and rapid isometric force characteristics as a tool to predict positional football playing ability, further research is needed. We hypothesized that peak force, time-specific areas of the force-time curve, and RFD phases would be different between the positions due to positional movements and requirements within the sport. Therefore, the purpose of the present study, was to assess positional groupings (skill, big skill, and line) for PF, PF at time-specific areas, and rate of force development during different phases of the force-time curve.

METHODS

Participants

Thirty-eight male collegiate athletes (mean ± *SD:* age 20.37 ± 1.62 years, height 185.37 ± 5.04 cm, and weight 101.89 ± 20.13 kg) volunteered to participate in the study. All participants were on roster with a division

II American collegiate football team, free of musculoskeletal injuries and had been participating in a structured off-season strength and conditioning program. All participants signed consent forms, which were approved from the Universities Institutional Review Board (2024-114).

Research design

Participants were assessed during their morning training sessions (0900 – 1400 hours) during phase 1 of off-season training in which athletes were not participating in on-field football practices. For each participant, testing was completed within one day in the following order: height and weight, and muscular strength. All assessments occurred after the participants completed an organized workout from the strength coach; no lower-extremity exercises were performed on the day of assessments.

IMTP testing protocol

All IMTP assessments were conducted on a Hawkin Dynamics force plate system (5th Generation; Westbrook, Maine, USA) with a sampling frequency of 1,000 Hz. The IMTP attempts were assessed using the testing protocols recommended by Comfort et al. (Comfort et al., 2019). Specifically, participants positioned themselves on the force plates where knee angle (125° - 145°) was confirmed using a goniometer. The lifting rack and placement of the bar was assessed and properly placed for each participant at a height that replicated the start of the second phase of a clean (Comfort et al., 2019). A standard 45lb. barbell (Legend Fitness Olympic Barbell, Knoxville, TN, USA) was positioned underneath safety racks secured to a weight rack (Legend Fitness, Knoxville, TN, USA).

For each IMTP attempt, the participant began by taking all the slack out of the barbell stoppers and leaving the body positioned in a locked manner. The test administrator began a three second countdown for the athlete. Once the participant began the pull, the administrator used verbal encouragement throughout the effort "*pull, pull, pull….*" During the IMPT attempts, participants were encouraged to pull as hard and fast as possible, the pull lasted approximately three seconds, and the participant was informed of when the test was completed. Three minutes of rest was allowed between each trial of the IMTP, with three total trials completed. If errors occurred within the testing protocol, an additional trial was completed for correct data results. All participants were able to complete their IMPT testing within 5 attempts.

Statistical analysis

Descriptive statistics, means and standard deviations were calculated for each variable. A one-way ANOVA with Bonferroni post-hoc adjustments was used to examine the group-specific positions OD/L (Line) (n = 16), LS (Large skill), (n = 9), and SS (Small Skill) (n = 13) for all dependent variables (PF, PF50 ms-PF250 ms, and RFD50 ms-RFD250 ms). The highest IMPT attempt per participant was used for statistical analysis. Statistical analyses were performed using PASW software version 28.0 (SPSS Inc, Chicago, IL, USA), and an alpha level of $p \leq .05$ was used to determine statistical significance.

RESULTS

Descriptive demographic information is expressed in Table 1.

Force

There was a significant difference for PF ($p \leq .001$; $\eta_p^2 = 0.540$), PF50 ($p \leq .001$; $\eta_p^2 = 0.503$), PF100 ($p \leq .001$; $\eta_p^2 = 0.398$), PF150 ($p \leq .001$; $\eta_p^2 = 0.500$), PF200 ($p \leq .001$; $\eta_p^2 = 0.500$), and PF250, ($p \leq .001$; $\eta_p^2 = 0.469$). Post-hoc analysis revealed OD/L and LS had greater PF compared to SS ($p \leq .001 – .026$), additionally, OD/L had greater PF compared to LS ($p = .022$). Significant differences for PF50-PF250 were seen where greater force was seen for OD/L and LS compared to SS ($p \leq .001 – .036$), and PF150 was greater for OD/L compared to LS ($p = .047$).

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Rate of force development

There was a significant difference for RFD 0-50ms (p = .004, η_p^2 = 0.267), while no differences were seen for any other RFD metrics (p = .061 – .252). For RFD 0-50 ms, post-hoc analysis revealed LS had greater RFD compared to SS and OD/L (p = .005 – .020).

Table 1. Mean and standard deviations (SD) demographic data of positions.

	Line (n = 16)		Big skill (n = 9)		Skill (n = 13)		*p*-value
	Mean	SD	Mean	SD	Mean	SD	
Age (yrs)	20.25	1.24	21.11	2.03	20.00	1.68	.271
Height (cm)	188.43	3.15	185.71	4.22	181.38	4.93	<.001*‡
Weight (kg)	121.00	11.15	99.07	9.20	80.33	6.38	<.001*‡†
Academic Class	1.88	0.89	2.78	1.20	1.85	1.28	.079

*Note. *Significantly greater (line vs. skill), ‡ Significantly greater (line vs. big skill), ‡ † Significantly greater (big skill vs. skill).*

DISCUSSION

Findings from the present study showed dissimilar force and rate of force development outcomes within a cohort of DII NCAA collegiate football players (grouped by position type). Significant differences were seen for all isometric force variables throughout a force time curve (Peak Force, PF50 ms, PF100 ms, PF150 ms, PF200 ms and PF250 ms) for OD/L and large skill compared to small skill players (Table 2), peak force and peak force at 150ms was greater for line compared to large skill athletes. When assessing rate of force development, large skill players possessed greater RFD 0-50 ms vs. line and small skill players (Table 3).

Table 2. Absolute Force mean (SD) maximum force (N) values for all time-specific time points for IMTP for all grouped positions.

	Peak force	PF50	PF100
Line	3546.13 ± 416.65	2278.44 ± 294.48	2674.88 ± 458.46
Big skill	3111.89 ± 327.84†	2322.33 ± 331.91	2664.56 ± 344.15
Skill	2668.31 ± 322.93*‡	1730.00 ± 208.20*‡	2049.77 ± 273.24*‡
	PF150	**PF200**	**PF250**
Line	2870.69 ± 377.96	2914.19 ± 287.46	2959.38 ± 367.67
Big skill	2550.22 ± 213.00†	2749.44 ± 366.09	2764.00 ± 328.62
Skill	2202.85 ± 241.11*‡	2269.38 ± 254.93*‡	2294.31 ± 254.69*‡

*Note. *Significantly greater (line vs. skill), † Significantly greater (line vs. big skill), ‡ † Significantly greater (big skill vs. skill).*

Table 3. Mean (SD) rate of force development (N.s-1) values for all time phases for IMTP for all grouped positions.

	RFD 0-50 ms	RFD 0-100 ms	RFD 0-150 ms
Line	9775.00 ± 4358.77∞	8851.88 ± 3984.13	7206.75 ± 2514.91
Big skill	15140.00 ± 6093.54	10992.22 ± 3281.36	6565.81 ± 1239.62
Skill	8466.15 ± 3162.79‡	7430.77 ± 2310.89	5974.31 ± 1478.96
	RFD 0-200 ms	**RFD 0-250 ms**	
Line	5622.50 ± 1481.01	4678.75 ± 1340.84	
Big skill	5920.56 ± 1638.96	4814.67 ± 1192.77	
Skill	4813.46 ± 1134.97	3950.46 ± 893.72	

Note. ∞ Significantly greater (big skill vs. line), ‡ Significantly greater (big skill vs. skill).

Peak force

Although PF is a common metric for discriminatory purposes (starter vs. non-starter) and sporting type (football, cyclists, rugby) (Johnson et al., 2025; McGuigan & Winchester, 2008; Thompson, Ryan, Sobolewski, Smith, Conchola, et al., 2013; Wang et al., 2016; West et al., 2011; Wilson & Murphy, 1995), findings from the present study observed significant differences for PF relating to positional grouping, where OD/L and LS players had greater PF compared to SS players. Additionally, PF was greater for OD/L compared to LS players. The present findings allows for one direct comparison (football groupings) where Johnson et al., (2025) reported no significant differences for PF between any of the positional groupings. These differences could be related to the overall sample size (16 vs. 38) dissimilar sample within each grouping (3 OD/L, 6 LS, 9 SS) vs. (16 OD/L, 9 LS, 13 SS), and status (starters vs. all athletes). Additionally, maximal IMTP testing protocols could also relate to the differences in findings (15-20 seconds of rest between attempts vs. 3 minutes rest). Be that as it may, there is a paucity of literature to compare the present IMTP findings to American football players (Johnson et al., 2025; McGuigan & Winchester, 2008), future research may want to assess IMTP with American football athletes across different collegiate levels (I, II, III, NAIA, JUCO), specifically, maximal force and rapid force characteristics, and if there are any differences within or between positions, playing status, etc.

Maximal force at specific time points

The present study observed significant differences for isometric force at specific time points of the force-time curve (PF50 ms, PF100 ms, PF150 ms, PF200 ms and PF250 ms), where OD/L and large skill had greater force compared to small skill players. Interestingly, pertaining to American football, and the IMTP, there is no previous literature that assessed early components of the force time curve (0-100 ms). When comparing the present study to a single joint maximum voluntary contraction Thompson et al., (2013) reported greater hamstring peak torque at 30ms for DI football starters compared to non-starters. While the present study did not assess status (starter vs. non-starter), the ability to produce force, quickly, is important for a multitude of athletic movements (Comfort et al., 2019). Pertaining to later force time curve epochs (i.e. >100 ms), Johnson et al. (2025) reported LS athletes had greater PF250 ms compared to SS players. These findings are somewhat similar, as the present study observed that both OD/L and LS players had greater PF250 ms compared to SS players. As previously mentioned, status (starter vs. entire sample), sample size (16 vs. 38) and IMTP protocol (15-20 seconds of rest between attempts vs. 3 minutes rest) could contribute to the dissimilar findings. Nevertheless, the present findings highlight the importance of being able to explosively apply forces, and to be able to attain the rapid and maximal force over the duration of the isometric contraction. For example, research suggests time specific force output relates to dynamic performance (Dos' Santos et al., 2017). Specifically, Dos' Santos, Jones, et al., (2017) found maximum power clean strength positively correlates with PF100 ms, PF150 ms, PF200 ms and PF250 ms when assessing rowing, soccer, bicycle motocross, and hockey athletes. While the aforementioned study included a variety of sporting types, their findings, coupled with the present study, highlight the importance of athletic performance occurring in a short amount of time (0-250 ms).

Rate of force development

Although a majority of coaching metrics want to assess strength, speed, and other observatory outcomes (Barker et al., 1993; Black & Roundy, 1994; Fry & Kraemer, 1991; Fry et al., 1991; Garstecki et al., 2004), RFD can allow coaches and researchers the ability to see the rate of force over specific durations (RFD 0-300 ms), and what factors may be contributing to the outcomes (skeletal or neural properties) (Aagaard et al., 2002; Andersen & Aagaard, 2006; Andersen et al., 2010). Although RFD, specifically early RFD (0-100 ms) has been shown to discriminate starters vs. non-starters in DI collegiate football players (Thompson, Ryan, Sobolewski, Smith, Conchola, et al., 2013), limited research has assessed RFD within collegiate

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football players (Johnson et al., 2025; McGuigan & Winchester, 2008; Thompson, Ryan, Sobolewski, Smith, Akehi, et al., 2013; Thompson, Ryan, Sobolewski, Smith, Conchola, et al., 2013). Authors that have assessed RFD with collegiate football players have shown a multitude of outcomes (weight room strength and athletic performance, starter vs. non-starter with early RFD, player groupings and RFD outcomes), however, only one study has looked at force time curve metrics, assessing both early and late RFD (Thompson, Ryan, Sobolewski, Smith, Conchola, et al., 2013), thus, the present study has limited studies to compare to. Nevertheless, when comparing positional groupings (SS, LS, OD/L) Johnson et al. (2025) reported significant differences for RFD 0-250ms, which LS had greater RFD compared to SS and OD/L. These findings are dissimilar to the present study, where RFD differences were only seen for early RFD (RFD 0-50ms), in which LS had greater RFD 0-50ms compared to other positional groupings. Potential differences could be related to sample size (16 vs.38) status (starters vs. non-classified), recovery between attempts (15-20 seconds of rest between attempts vs. 3 minutes rest). While athletic status for collegiate football players comprises a wide range of metrics (strength, speed, power, agility, body composition) it is highly suggested that future research assesses force time metrics (both early and late), with starters vs. non-starters, as well as positional groupings.

Regardless of position, or status (starter vs. non-starter), maximum force throughout a force-time curve can be advantageous for positions on the field and can aid with program design for strength coaches. Future studies may want to assess maximum force, and force time curve characteristics with force plates, and may want to measure said metrics throughout different portions of a season (In, Off, Post, Pre), how force time curve for strength/force is impacted within a competitive season, or pre- and post- testing of a training mesocycle. The present study, and Johnson et al., (Johnson et al., 2025) (both using portable force plates) reported early and overall RFD being higher for LS athletes compared to their cohorts. However, future research is needed over said variables, with other American football players.

CONCLUSION

When assessing said strength and rate of force development by positional grouping (OD/L, LS, SS), differences were seen, specifically where PF was significantly greater for OD/L and LS vs. SS players. Further, OD/L had greater PF than LS players and PF at 150ms was greater for line compared to large skill athletes. When looking at PF across specific time points (PF50-PF250 ms), OD/L and LS players had greater force than SS players. Assessing RFD showed RFD 50 ms was greater for LS compared to OD/L. Findings from the study indicate the importance of assessing strength, and rate of force development from an maximal IMTP contractions while using force plates. This assessment allows for further comprehension of force-time curve metrics, per individuals, or groupings within an athletic team. It also provides insights into the physiological aspects of differing roles and the needs that each possess within their position. Although assessing athletes with force plates would be ideal in all practical settings, this is not a practical purchase for all levels of strength and conditioning professionals. The findings from the current field of research and this study can help to further explain the connection that needs to be made with increasing force and rate of force production in the development, progression, and specificity of training competent athletes for their position needs.

AUTHOR CONTRIBUTIONS

Data curation by E.C., T.R.; formal analysis, E.C., and T.R. Conceptualisation, E.C., T.R. Methodology, E.C., T.R., R.W., A.W., M.N. Investigation - E.C., T.R., R.W., A.W., M.N. Writing—original draft preparation, E.C.

and T.R. Writing—review and editing, T.R., R.W., A.W., and M.N. All authors commented on previous versions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

INSTITUTIONAL REVIEW BOARD STATEMENT

The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board from the University of Central Oklahoma (2024-114, dated 12.05.2024).

INFORMED CONSENT STATEMENT

Informed consent was obtained from all participants involved in the study and their parents/guardians.

DATA AVAILABILITY STATEMENT

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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ORIGINAL ARTICLE

Benchmarking tactical efficiency in international football: Identifying gaps and strategic improvements

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ABSTRACT

This study evaluates the tactical efficiency of the South Korean national football team using a modified output-oriented BCC Data Envelopment Analysis (DEA) model, by benchmarking its performance against reference teams grouped by continental classifications. Among the four reference groups, America and Europe group produced feasible solutions. South Korean national football team consistently underperformed in converting tactical inputs into goals. In several cases indicating that the team would need to double its goal output—given its current resource level—to match benchmark efficiency. This research contributes methodologically by reinterpreting Ø as a goal-scaling factor and slack variables as diagnostics for tactical inefficiencies. As such, DEA proves valuable not only for internal efficiency evaluation but also for strategic benchmarking in high-performance football contexts. This study offers a DEA-based framework to evaluate tactical efficiency by comparing teams' resource usage and outcomes across formations and tournament stages. It benchmarks the target team against efficient team combinations to identify tactical gaps and input shortfalls. The findings provide strategic guidance by quantifying areas for improvement and suggesting optimal resource.

Keywords: Performance analysis, Football, Efficiency, DEA, Optimal, Benchmark.

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INTRODUCTION

The FIFA World Cup is the most prominent and widely viewed international sporting event, drawing participation from 32 national teams across eight groups. Following the group stage—where the top two teams from each group advance—the tournament adopts a single-elimination format, culminating in a final match that determines the world champion. Given the high level of competition and global representation, the World Cup offers a unique lens through which to analyse tactical diversity, strategic preferences, and the developmental trajectories of national football programs across continents.

FIFA World Cup performance analysis encompasses both individual and collective dimensions, and extensive research has explored the key factors associated with success in matches. Studies focusing on offensive metrics typically emphasize variables such as shot frequency, shot accuracy, and passing effectiveness, whereas defensive performance is commonly assessed through measures like tackles and clearances. However, the exclusive use of indicators such as shot count, possession percentage, and number of passes presents inherent limitations in capturing the full complexity of team performance.

At the 2018 FIFA World Cup in Russia, Germany was eliminated in the group stage after a 2–0 defeat to South Korea, despite recording 16 more shots and completing 476 more passes. Similarly, at the 2022 FIFA World Cup in Qatar, Japan secured a 2–1 victory over Spain and topped their group, even though they registered eight fewer shots and 846 fewer passes. Additionally, one of the most unexpected results of the 2022 tournament occurred when Saudi Arabia defeated eventual champions Argentina 2–1 in the group stage.

These surprising outcomes highlight that traditional match statistics alone may not fully reflect tactical effectiveness. To address this gap, the present study moves beyond match-level data and proposes a structured benchmarking framework based on regional team classifications. By clustering reference teams the study interprets λ-weighted combinations not just as efficiency references, but as practically meaningful tactical archetypes.

Furthermore, the inclusion of slack variables enables a more granular analysis of tactical resource utilization, identifying specific areas where input variables—such as shots, effective shots, or passes—fall short of benchmark standards. This allows for a diagnostic perspective on how much tactical adjustment is required to reach desired performance levels.

By reframing the output-oriented BCC DEA model as a means of evaluating "*tactical implementation efficiency*," this research shifts the focus from static efficiency rankings to actionable insight. In doing so, the study contributes a novel analytical framework that links benchmarking efficiency with tactical feasibility and strategic planning. This approach underscores the importance of region-specific benchmarking in formulating adaptable and competitive tactical strategies. Using a modified output-oriented BCC Data Envelopment Analysis (DEA) framework, this research aims to identify areas of tactical inefficiency and potential improvement, with the goal of informing future strategic planning and training optimization.

The remainder of this paper is structured as follows. Section 2 reviews the relevant literature and Section 3 describes the methodology and variable selection for the efficiency analysis. Section 4 presents the empirical findings, including descriptive statistics and benchmarking outcomes. Finally, Section 5 discusses the implications of the results and offers concluding remarks along with directions for future research.

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This paper conducted an analysis targeting the Korea National Football team that advanced to the FIFA WORLD CUP, and the current status of various previous studies is as follows. Numerous variables influence outcomes and rankings in football matches. While a substantial body of research has examined these factors within the context of league competitions, relatively fewer studies have focused on tournament settings.

Many researchers have studied shooting indicators. A range of empirical studies has highlighted key performance indicators related to successful outcomes in international football tournaments. Liu (2015), examining data from the 2014 FIFA World Cup, found that both the number of shots and shots on target were positively associated with the probability of winning. Similarly, Danilo (2019) reported that winning teams in the 2018 World Cup exhibited higher passing accuracy, along with increased shot attempts and shots on target. Complementing this, Lago-Ballesteros and Lago-Peñas (2010) noted that leading teams generally achieved more goals, as well as a greater number of total and accurate shots. Building on these findings, Lago-Peñas, Lago-Ballesteros, and Rey (2011) identified shot volume—particularly shots on target—as a distinguishing factor between winning and losing teams.

Several scholars have investigated the role of passing in determining match outcomes. Collet (2013) emphasized the importance of pass efficiency, particularly those passes that directly contribute to goal-scoring opportunities, as a critical factor in team success. Harrop and Nevill (2014) argued that a reduced number of total passes, especially those executed in the attacking half, were positively associated with winning matches. More recently, Rossi et al. (2019) asserted that the effectiveness of passing plays a more decisive role in match performance than simple ball possession.

Efficiency-related metrics have been the focus of several key studies in football performance analysis. Broich et al. (2014) highlighted the critical role of goal efficiency in determining team success within Germany's top-tier league. In the context of Korean professional football, Hwang (2022) demonstrated that overall match efficiency had a positive influence on a team's seasonal performance. Expanding this line of inquiry, Hwang (2024) identified both passing and shooting efficiency as significant contributors to improved performance outcomes in Italy's Serie A. Furthermore, Hwang (2025) reported that efficiency metrics played a decisive role in differentiating winning and losing teams in the quarterfinal and semifinal stages of UEFA EURO 2024.

Previous studies have primarily focused on comparative analyses of efficiency metrics to evaluate relative team rankings within leagues or to distinguish winners from losers in tournament matches. However, such research has been limited to descriptive assessments without further exploration of strategic implications.

This study distinguishes itself from previous research in several key aspects.

First, rather than merely calculating efficiency scores, it focuses on the South Korean national team as the primary subject of analysis and incorporates an evaluation of input resources to identify suitable benchmark teams.

Second, by deriving these benchmark teams, the study proposes a quantitative methodology that not only assesses efficiency but also provides strategic recommendations for improving the tactical structure and overall strategy of the Korea team.

Third, the research further extends its scope by grouping teams based on region (e.g., Europe, America) thereby enabling a structured benchmarking analysis across multiple dimensions.

METHODOLOGY

Data

This study is based on an analysis of the 32 group stage matches played by the 32 national teams that qualified for the FIFA World Cup. All match data is presented in Table 1.

Table 1. Match data.

Nations	Number of shots	Number of effective shots	Number of success passes	Goal
Argentina	43	20	1754	5
Australia	21	7	802	3
Belgium	35	9	1530	1
Brazil	57	21	1462	3
Cameroon	28	16	895	4
Canada	35	5	1205	2
Costa Rica	12	7	770	3
Croatia	29	16	1394	4
Denmark	34	10	1505	1
Ecuador	30	11	1076	4
England	39	17	1713	9
France	54	17	1601	6
Germany	69	24	1595	6
Ghana	26	10	913	5
Iran	33	10	700	4
Japan	31	10	848	4
Mexico	41	16	1011	2
Morocco	24	8	842	4
Netherlands	25	8	1491	5
Poland	19	5	701	2
Portugal	39	14	1555	6
Qatar	20	6	1051	1
Saudi Arabia	29	9	803	3
Senegal	42	12	920	5
Serbia	32	9	1098	5
South Korea	42	13	1062	4
Spain	36	16	2489	9
Switzerland	27	10	1155	4
Tunisia	32	8	901	1
United States	28	7	1244	2
Uruguay	33	11	1078	2
Wales	24	7	955	1

Effective game strategies that maintain offensive momentum through passes into the goal opportunity can contribute to winning. From an efficiency perspective, a team that executes few passes while making numerous attacks may demonstrate high game efficiency. The shot and pass success rate data for the 2022 FIFA World cup teams are presented in Table 2.

Although football analytics increasingly relies on numerical performance indicators, these raw statistics frequently fall short in explaining how tactical efforts translate into actual match results. For instance, during the 2022 FIFA World Cup group stage, teams averaged 33.4 shots, 11.5 shots on target, and 1,191 successful passes per match, resulting in an average of 3.75 goals. However, the overall shot success rate

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stood at only 34%, while the goal success rate was just 32%.

These figures highlight a significant efficiency gap between offensive effort and scoring outcomes, reinforcing the need for analytical approaches that assess not only the volume but also the transformation efficiency of tactical actions.

Table 2. Shot / pass success rate.

Shot success rate (Number of shots on target / shots)	Goal success rate (Goals/Number of shots on target)
34%	32%

Table 3. Group stage matches data.

Division	Average	Standard Deviation	Minimum value	Maximum value
Shooting	33.4	11.5	12	69
Effective shot	11.5	4.86	5	24
Number of success passes	1191	395	700	2489
Goal	3.75	2.08	1	9

Methods

Data Envelopment Analysis (DEA) is a non-parametric method used to assess efficiency by comparing the inputs and outputs of decision-making units (DMUs). It evaluates the performance of each DMU relative to a peer group, identifying whether it operates efficiently or inefficiently. By employing linear programming, DEA measures the relative efficiency of each unit based on its distance from the efficiency frontier. This approach has been widely applied in prior research to analyse the performance efficiency of football teams. (Espitia-Escuer & García-Cebrian, 2004; Espitia-Escuer & García-Cebrián, 2010; García-Sánchez, 2007; Haas et al., 2004; Haas, 2003;Hwang, 2022; Hwang, 2024: Hwang, 2025; Rossi et al., 2019; Tenga et al., 2010).

Efficiency in DEA is measured on a scale ranging from 0 to 1, facilitating relative comparisons among decision-making units (DMUs). A score closer to 1 signifies higher efficiency, whereas lower-scoring DMUs can pinpoint inefficiencies in their input usage or output production. Conventional BCC models primarily focus on relative efficiency assessments among internal DMUs and do not readily allow for quantitative interpretation of the benchmark units.

$$\max \emptyset + \varepsilon \left(\sum s^{-}{}_{i} + \sum s^{+}{}_{r} \right)$$

$$s.t$$

$$\sum_{i=1}^{n} \lambda_j x_{ij} = x_{io} + s_i^-$$

$$\sum_{i=1}^{n} \lambda_j y_{rj} = \emptyset \cdot y_{io} + s_r^+$$

$$\sum_{i=1}^{n} \lambda_j = 1$$

$$\lambda_j \geq 0, \quad s_i^-, s_r^+ \geq 0, \quad \emptyset \geq 0$$

Table 4. Symbol Definitions for the Output-Oriented BCC DEA Model.

Symbol	Description
Φ	Output-oriented efficiency score
ε	A very small positive value used to penalize slack in the objective function
j	DMU(National Team)
λ_j	Weight assigned to DMU j (used in convex combinations)
$X_{i,j}$	Value of input variable i for DMU j
i	Input value (shots, shots on target, success pass)
r	Output value (goal)
$X_{i,o}$	Value of input variable evaluated DMU_0
$Y_{r,j}$	Value of output variable i for DMU j
$Y_{i,o}$	Value of output variable evaluated DMU_0
S_i^-	Input slack for variable (shots, effective shots, passes)
S_r^+	Input slack for variable (goal)
n	Total number of DMUs

This study adopts a modified output-oriented BCC DEA model based on the envelopment form but redefines the benchmarking framework by introducing externally defined target input-output values.

Unlike the conventional DEA which evaluates internal DMUs against the efficient frontier, this model assesses how closely a specific team (South Korea) can approach a predefined strategic performance target by forming a λ-weighted combination of efficient peer teams. While preserving the mathematical structure of the traditional BCC envelopment model, the proposed approach reinterprets Ø not merely as a radial expansion factor, but rather as a strategic amplification coefficient for achieving target outcomes. Furthermore, slack variables are recontextualized to represent the shortfalls in tactical resources required to meet performance goals. This enhanced perspective enables the model to function as a tactical benchmarking tool for decision support in fields such as sports analytics.

Table 4. presents the definitions of all variables and parameters used in the output-oriented BCC DEA model. The inputs (shots, shots on target and passes) are indexed by i, while the output (goals scored) is denoted by r. Slack variables represent the shortfall in achieving efficient performance under the benchmark configuration. This study adopts the number of total shots, shots on target, and successful passes as input variables, based on prior research identifying these factors as key contributors to match outcomes. The primary aim is to develop a benchmarking model that enables the evaluation of tactical efficiency and the derivation of strategic implications for improvement. To achieve this, 32 national teams were grouped according to continental classifications.

RESULTS

In this study, teams were categorized by continent into four groups: Asia, Africa, Europe, and the Americas. The Asia group consisted of Australia, Iran, Japan, Qatar, and Saudi Arabia. The Africa group included Cameroon, Ghana, Morocco, Senegal, and Tunisia. The Europe group comprised Belgium, Croatia, Denmark, England, France, Germany, Netherlands, Poland, Portugal, Serbia, Spain, Sweden, and Wales. The America group, considering sample size, incorporated both South and North/Central American teams, including Argentina, Brazil, Canada, Costa Rica, Ecuador, Mexico, United States, and Uruguay.

Among the multiple reference groups constructed for benchmarking, 2 Group were selected for in-depth analysis: one group based on Europe and another is America.

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Asia and Africa group had resulted in an infeasible solution under the given input-output targets. While the DEA model for the Europe and America group converged to a feasible optimal solution ($\emptyset = 1.2$ $\emptyset = 2.1$) the model.

In the case of the infeasible reference group, the target unit's output target (e.g., 6 goals) could not be reproduced by any convex combination of the Asia and Africa as none of their λ-weighted projections reached the target output level. For instance, the λ combination of all reference units yielded a maximum goal output of 4.8, falling short of the target team's actual goal (6), while requiring more input (pass counts exceeding 1000). This suggests that the South Korea team performance lies outside the production possibility set defined by the benchmark units, thereby resulting in infeasibility. Two specific benchmark configurations—America and Europe—yielded Ø values of 1.2 and 2.1, respectively, highlighting notable variation in required output expansion to reach efficient frontiers.

The analysis results are shown in Table 6. The America group presented a comparatively moderate resource demand, with an efficiency coefficient (φ) of 1.25, indicating that only a 25% increase in goal output would be sufficient for the team to reach the benchmark efficiency level. The efficiency score was 0.80, which is higher than that of the European group, and the λ-combination included multiple reference teams such as Argentina, offering a more realistic strategic alternative. The slack values indicated a shortfall of approximately 7 effective shots and 692 successful passes, suggesting a relatively lower input burden compared to the European benchmark. In contrast, the Europe group presented significantly higher resource demands, with Ø = 2.1, suggesting that while the tactical model is theoretically more productive.

In Europe Group (Ø = 2.1, efficiency score = 0.47), the DEA model projected that the target team would need to increase its goal-scoring output by about 110% to match the benchmark efficiency level. Slack analysis revealed shortfalls of approximately 4 effective shots and 1,264 successful passes compared to the benchmark, implying that a substantially higher level of tactical input would be required to achieve comparable performance. In contrast, America (Ø = 1.25, efficiency score = 0.8) presented a considerably more attainable benchmark. Here, the required expansion in goal output was 25% increase, with comparatively lower input slack: 7 effective shots and 692 passes. Compared to the America group, European teams exhibited significantly higher levels of successful passes and effective shots but required a greater increase in output (φ = 2.1) to reach the efficiency frontier. This suggests that while the European tactical model is theoretically productive, its practical feasibility may be limited for the target team.

Therefore, from a strategic feasibility perspective, the America-based benchmark appears to be more compatible and actionable for the South Korea team. It further reinforces the need for strategic adjustments in shot efficiency and pass success to align more closely with high-performing benchmark teams. These findings underscore the utility of DEA not only as a diagnostic tool for internal performance efficiency but also as a strategic instrument for external benchmarking. By treating Ø as a performance scaling coefficient and slack variables as indicators of tactical inefficiency, the model enables a nuanced understanding of where and how improvements can be realistically pursued.

Table 5. Group 4 results.

Group	Status	Φ
Asia	Infeasible	-
Africa	Infeasible	-
America	Feasible	1.25
Europe	Feasible	2.11

Table 6. Group 2 results.

	Group1(America)	**Group2(EUROPE)**
Φ	1.25 (0.80)	2.11 (0.47)
Shots(slack)	-	-
Effective shots(slack)	7	4.45
Pass(slack)	692	1,264
Goal	5	8.45
Benchmark Team	Argentina (λ_j = 1.0)	Spain (λ_j = 0.8) Germany (λ_j = 0.2)

CONCLUSIONS

This study investigates the efficiency of a South Korea national football team by comparing its performance against multiple reference groups using a modified output-oriented BCC Data Envelopment Analysis (DEA) framework. Through this approach, the study evaluates how tactical resources—namely total shots, effective shots on target, and success pass—translate into scoring output when benchmarked against internationally recognized team configurations. Among the four groups, Asia and Africa group resulted in an infeasible solution under the given input-output targets.

The infeasibility observed in two of the reference group configurations highlights a fundamental limitation in tactical alignment between the target team and the selected benchmark units. Specifically, the target inputs and outputs could not be expressed as a convex combination of the reference DMUs, which implies that either the performance target was unrealistic within the data envelope or the reference set lacked sufficient structural diversity. In such cases, infeasibility meaningful outcome that signals limited strategic compatibility.

The analysis reveals that across most reference groups, the team consistently underperformed in its transformation of tactical inputs into goals. Notably, several configurations required a Ø coefficient greater than 2.0, implying that, under ideal benchmark conditions, the team could potentially double its scoring output with more effective deployment of similar or modestly improved resources. This gap underscores both a tactical inefficiency and an opportunity for targeted performance enhancement.

Among the evaluated groups, the configuration derived from Argentina National team produced the most efficient projection (Ø = 1.25, efficiency score = 0.80), indicating minimal performance adjustment needed. This suggests that adopting strategies closer to that configuration may yield realistic and actionable improvements within the team's current resource capacity. In contrast, configurations referencing teams from Europe—despite indicating higher theoretical goal productivity—demanded significantly greater input levels, potentially reducing practical feasibility.

From a methodological perspective, the study extends the utility of DEA beyond conventional internal efficiency analysis. By using DEA as a strategic benchmarking instrument, the Ø coefficient is reinterpreted as a goal-scaling factor, and slack variables provide granular diagnostic insights into resource deficiencies across key tactical areas. This innovative application supports evidence-based coaching and tactical planning in high-performance sports contexts.

Furthermore, the findings open avenues for broader application. Future studies can explore additional input dimensions, such as assists, defensive interceptions, and off-the-ball movements, to capture holistic team dynamics. Comparative analysis across tournaments—including the World Cup, Copa America, or AFC

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Asian Cup—could also enrich our understanding of continental tactical typologies. Ultimately, refining DEA models to accommodate complex match dynamics can foster deeper insights into strategic efficiency and performance optimization in elite football.

This study contributes to the field by offering a structured framework to quantitatively evaluate the resource configurations and tactical outcomes of teams advancing through each stage of international tournaments. By benchmarking against tactically efficient team combinations across various formations and regional groupings, the model enables a precise diagnosis of the target team's tactical deficiencies and input shortfalls. Consequently, it provides actionable insights for strategic improvement by identifying optimal tactical compositions and resource adjustments required to enhance performance.

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ORIGINAL ARTICLE

How do match location and opponent level influence complex I offensive strategy in men's volleyball? The case of the Brazilian Men's Superleague

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ABSTRACT

Match analysis identifies patterns in both defensive and offensive systems and key performance parameters, which should be applied in the practice context. This study examined the offensive game patterns in high-level Brazilian men's volleyball, considering the opponent's ranking and match location. The sample comprised twenty-two matches involving the top four teams competing against each of the twelve participants in the 2021/2022 Brazilian Men's Volleyball Superliga. Each team played both home and away matches, leading to an analysis of 1,699 Complex I attack actions. The results indicated that the highest eigenvector centrality values were observed for settings primarily directed to positions 3 and 4, regardless of the opponent. Attacks were typically executed by the middle blocker positioned in front of and near the setter against single blocks, frequently resulting in points. Variations were observed depending on the team's rotation and the set phase. High-level Brazilian volleyball teams exhibited minimal variations in their Complex I offensive strategies. However, finalist teams demonstrated differences in the distribution and attack patterns of the middle blocker.

Keywords: Performance analysis, Game complex, Match analysis, Network analysis, Team sports.

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INTRODUCTION

Match Analysis is a valuable tool in sports, allowing for the identification of key performance parameters that contribute to team success. This analytical approach facilitates the structuring and adaptation of training programs or competitive environments to maintain or enhance observable performance (Drikos et al., 2021, 2022; Laporta et al., 2023; Martins et al., 2021). Match analysis is well established in the literature and has evolved to incorporate more contextualized assessments, applying an ecological perspective to sports performance (Giatsis et al., 2023; Lima et al., 2023). Within this framework, match analyses that overlook contextual factors such as opponent level and match location fail to fully capture the complexity of competitive dynamics (do Nascimento et al., 2024; Ribeiro et al., 2022; van Meurs et al., 2023; Yu et al., 2020, 2021).

Studies indicate that match location significantly impacts game patterns in volleyball, with home and away matches exhibiting differences in team performance (Pollard et al., 2017). This effect is attributed to crowd influence on players' performance (Pollard et al., 2017; van Meurs et al., 2023). The prevailing assumption is that a larger benefits the home team while disadvantaging the away team. This idea gave rise to the social support hypothesis, suggesting that higher spectator density creates an intense supporting atmosphere, which could translate into improved performance (van Meurs et al., 2023). Given the likelihood that match location influences game dynamics, it is essential to account for this factor when analysing offensive and defensive performance in volleyball. Elements such as familiarity with the environment, crowd support, and psychological advantages for the home team can directly impact decision-making, technical execution, and tactical strategy. Ignoring this influence may introduce bias into performance assessments. Playing at home has increased the likelihood of victory compared to away matches, which is more pronounced in men's competitions (Pollard et al., 2017; van Meurs et al., 2023). The home advantage is likely influenced by travel-related fatigue, familiarity with the playing venue, referee bias, tactical adjustments, psychological factors, and other contextual elements (Pollard, 2008).

Furthermore, when analysing sports performance in volleyball, it is essential to account not only for technical, tactical, and match location but also for the opponent's level, as game patterns also depend on the adversary's quality (Drikos et al., 2022). Regarding volleyball, research has evolved from generalized analyses that consider all teams in a tournament to more team-specific assessments (Rocha, Laporta, Rodrigues, de Lira, et al., 2023; Rocha, Laporta, Rodrigues, Guimarães, et al., 2023).

Team-specific analyses reveal that in world championships, higher-ranked teams exhibit superior reception quality, allowing for more structured offensive plays with faster and more powerful attacks, with the championship-winning team scoring more points than others (Rocha, Laporta, Rodrigues, Guimarães, et al., 2023). However, variations exist in game strategies among international teams, as higher-ranked teams tend to accelerate plays even in suboptimal situations, diversify their attack options, and opt for powerful attacks following consecutive opponent errors (Martins et al., 2022).

An analysis of the European Men's Volleyball Championship indicated that match performance and final tournament rankings influence game patterns (Drikos et al., 2022). The primary performance indicators distinguishing winning and losing teams vary, as matches between teams of different levels tend to feature more opponent errors, whereas evenly matched teams prioritize avoiding blocked attacks (Drikos et al., 2022). However, it remains unclear whether this effect is indeed due to the quality of the opponent, as other factors may influence it, such as the stage of the competition or the execution of performance aligned with training routines. Therefore, further studies are needed to understand the impact of opponent quality better, considering other scenarios, such as national-level matches. In Brazilian volleyball, studies have shown that

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reception quality affects offensive organization, set location, and game strategy (Costa et al., 2016). However, offensive patterns do not appear to be significantly influenced by the opponent's level, as setters tend to favour traditional, low-risk strategies to minimize errors (Nascimento, Laporta, Pedrosa, et al., 2023). Analysing performance about match location is essential to understanding potential variations in this pattern. A comprehensive evaluation considering the match location and the opponent's rankling will provide deeper insights into this issue.

Given these findings, analysing team-specific offensive patterns in men's volleyball is crucial while considering match location to avoid overgeneralization and account for the home-court advantage observed in this sport. Based on this context, the present study aims to analyse the offensive game patterns of high-level Brazilian men's volleyball, considering the opponent's ranking and whether the match was played at home or away. The study proposes the following hypotheses: 1 - In home matches, higher eigenvector centrality values will be observed for sets directed to position 3, with the middle blocker positioned in front of the setter, against a single block, resulting in attack points; 2 - In away matches, higher eigenvector centrality values will be observed for sets directed to positions 4 and 2, against a double block, resulting in attack points; 3 - Differences in offensive patterns will be observed depending on the opposing team.

METHODS

Sample

This study examined twenty-two matches featuring the top four teams competing against each of the twelve participants in the 2021/2022 Brazilian Men's Volleyball Superliga. Each team engaged in both home and away matches, resulting in the analysis of 1,699 Complex I attack actions. The Complex I Attacks corresponding on attacks initiated following receptions that enabled structured offensive plays with multiple attack options (Hurst et al., 2016).

Variables

Setter's initial position

The onset of each rally was analysed, with rotations categorized from Rotation 1 (R1) to Rotation 6 (R6). The setter's position offers insights into the offensive structure, as all teams utilized a 5-1 offensive system. For instance, in R1, three attackers were positioned at the net, with the opposite hitter in position 4 and the outside hitter in position 2.

Middle-blocker attack location

The attack location of the middle-blocker was categorized based on the spatial position relative to the setter. The attack could occur in front of and near the setter (TF), behind and near the setter (TC), or in front but at a greater distance from the setter (T7) (Costa, Ceccato, Evangelista, et al., 2016; Fellingham et al., 2013).

Setting distribution

To evaluate how setters allocated the ball across offensive zones, the study considered sets directed to zones 4 (SETT-P4), 3 (SETT-P3), 2 (SETT-P2), 1 (SETT-P1), and 6 (SETT-P6). Additionally, attacks executed by the setter on the second contact, including setter dumps, were recorded (2SETT).

Attack efficacy

The outcomes of attacks were classified into four categories: (1) error, where the attacker committed a fault such as hitting the net, sending the ball out of bounds, or violating regulations; (2) blocked, where the opponent successfully neutralized the attack; (3) continuation, where the attack allowed a counterattack

without immediately determining the point; and (4) point, where the attack directly resulted in a score by either landing in the opponent's court or deflecting off the block out of bounds (Marcelino et al., 2011).

Number of blockers

The number of blockers was recorded to assess the impact of the setter's distribution on subsequent actions. Blocking formations were categorized as follows: triple block [1 × 3], broken triple [1 × (2 + 1)], double block [1 × 2], broken double [1 × (1 + 1)], single block [1 × 1], or no block, where the setter effectively prevented a blocking attempt [1 × 0] (Rocha et al., 2020).

Moment of set

Furthermore, the study examined different phases of the game set, categorizing them as follows: the initial phase (INI), ranging from 0 to 8 points; the middle phase (MED), spanning from 9 to 16 points; and the final phase (FIN), starting from the 17th point until the conclusion of the set. For the analysis of the fifth set, the classification was adjusted accordingly: the INI phase included 0 to 5 points, the MED phase covered 6 to 10 points, and the FIN phase encompassed all points from the 11th onward until the set's completion.

Data collection

Match footage was obtained using a Sony® high-definition (1080p) camera, positioned 7 to 9 meters behind the end line and elevated 5 meters from the ground to capture a bird's-eye perspective of the court. The analysis was conducted by three physical education professionals, each with over five years of experience in performance analysis. To ensure reliability, 30% of the recorded actions were re-evaluated, exceeding the standard reference of 10% (Tabachnick & Fidell, 2013). Intra-observer reliability was confirmed with a Cohen's Kappa coefficient of 1 (standard error = 0), while inter-observer reliability values ranged from 0.93 to 0.99 (standard errors of 0.03 and 0.01, respectively), all surpassing the recommended threshold of 0.75 (Fleiss et al., 2013). These recordings were provided by the Brazilian Volleyball Team's technical staff.

Data analysis

Eight networks were constructed using Social Network Analysis and Eigenvector Centrality (Bonacich, 2007), with two networks examined per team representing home and away matches. Data were compiled in a Microsoft Excel 2015 for Windows spreadsheet, followed by quality checks and exploratory statistical analysis using IBM SPSS Statistics (version 23, Armonk, NY, USA). Social network analysis used Gephi 0.8.2-beta for Windows (version 10.10.3, France). This methodological approach was selected for its capacity to evaluate the connectivity and complexity of interactions among all variables, providing a comprehensive perspective (Borgatti, 2005).

Eigenvector centrality was employed to determine node importance within the network, considering the number of direct connections and the centrality of interconnected nodes (Bonacich, 2007; Borgatti, 2005). The visualization of eigenvector values was achieved by adjusting node sizes and edge thicknesses, ensuring a proportional representation of importance within the network. Both direct and indirect connections between variables were highlighted (Laporta et al., 2018a, 2018b). To optimize network organization, the Fruchterman-Reingold algorithm was implemented (area set to 100,000), positioning nodes with the highest eigenvector centrality at the centre of each subnetwork (Newman, 2006).

Supplementary material details the eigenvector values per team and match. Nodes representing home matches are prefixed with 'H,' while those for away matches begin with 'A.' Additionally, matchups were labelled according to the ranking positions of competing teams. For example, in a game where Team 1 played at home against Team 10, nodes were labelled "*H_01x10*." For middle-blocker attack locations, the

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corresponding nodes were denoted as "*H_01x10_TF*," "*H_01x10_TC*," "*H_01x10_T7*," and "*H_01x10_2SETT*."

RESULTS

Considering the extensive volume of results (Table1, provided upon request), we present only the nodes with eigenvector values equal to or greater than 0.9 for home matches (Figure 1) and away matches (Figure 2). For the 1st place team, in home matches, the highest eigenvector values were observed in the game against the 5th place team, specifically for the variables attack point (1.00), middle attack in front and far from the setter (0.97), and attacks occurring at the end of the set (0.92). In away matches, the highest eigenvector values were recorded in the game against the 3rd place team, particularly for attack point (0.95) and attack continuity (0.93), middle attack in front and far from the setter (0.92 and 0.96, respectively), as well as for attacks occurring at the beginning (1.00) and end of the set (0.95).

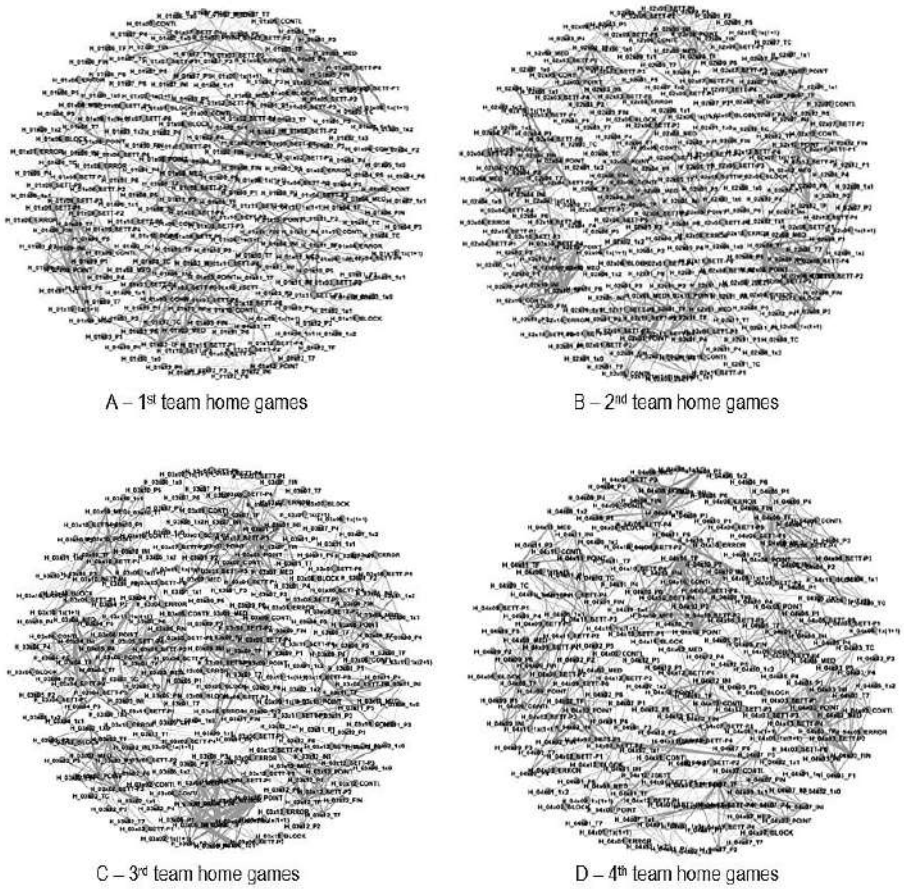
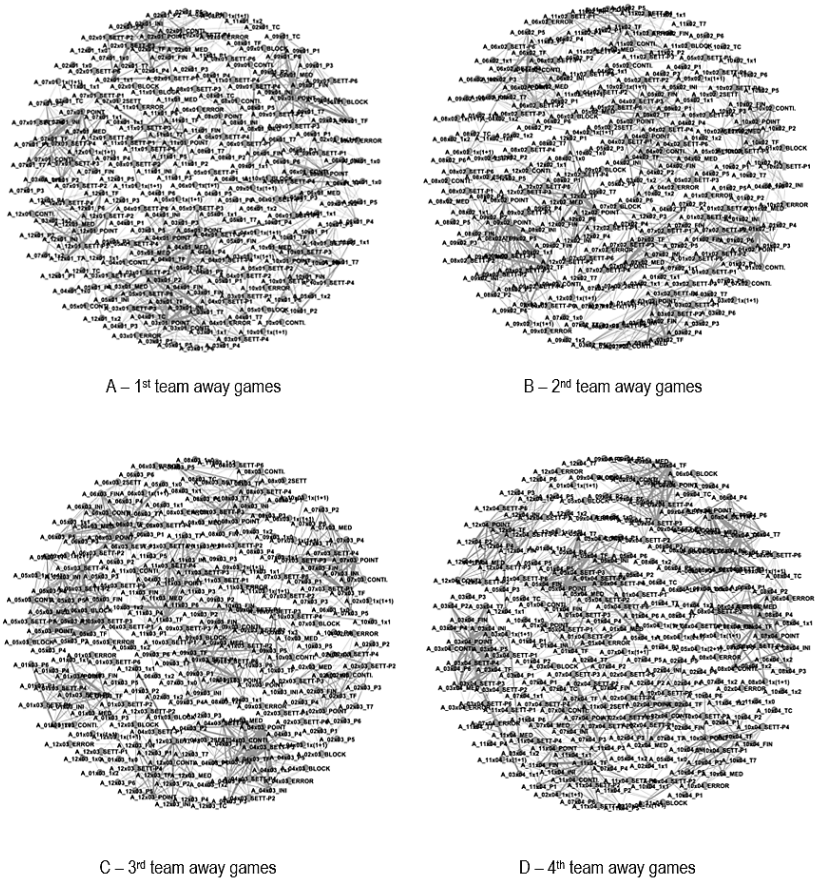


Figure 1. Eigenvector values for games played at home by teams ranked 1st to 4th.

For the 2nd place team, in home matches, the highest eigenvector values were found in the game against the 6th place team, particularly for the middle attack in front and close to the setter (1.00), attacks occurring at the end of the set (0.93), and attacks resulting in continuity (0.95) or points (0.95). In away matches, the highest eigenvector values were recorded for middle attack in front and close to the setter against both the 2nd place team (0.99) and the 6th place team (1.00), as well as for attack point against the 6th place team (0.95).



A – 1st team away games

B – 2nd team away games

C – 3rd team away games

D – 4th team away games

Figure 2. Eigenvector values for games played away from home by teams ranked 1st to 4th.

For the 3rd-place team, in home matches, the highest eigenvector values were observed in the game against the 6th place team, specifically for middle attack in front and close to the setter (1.00), middle attack in front and far from the setter (0.98), sets to positions P3 and P4 (0.91 for both), attacks occurring in the middle of the set (0.94), and attack point (0.93). In away matches, the highest eigenvector values were found against the 5th place team, specifically for the middle attack in front and close to the setter (1.00) and attack point (0.92).

For the 4th-place team, in home matches, the highest eigenvector values were observed in matches against the 3rd and 10th-place teams, specifically for middle attacks in front and close to the setter (0.99 and 1.00, respectively), attacks occurring at the end of the set (0.943 for both), and attack points (0.99 and 0.93, respectively).

DISCUSSION

Match analysis assists coaches in developing training programs and evaluating the strengths and weaknesses of their teams (González-Rodenas et al., 2019; Silva, Marcelino, et al., 2016). The current literature includes numerous studies analysing volleyball matches (Fernandez-Echeverria et al., 2019; García-de-Alcaraz & Marcelino, 2017; Marcelino et al., 2011; Silva et al., 2013). However, most of these analyses are general and do not capture the nuances that influence team performance indicators (García-de-Alcaraz & Marcelino, 2017; Lima et al., 2023; Millán-Sánchez et al., 2019). Furthermore, factors such as match location and type of competition can influence performance (van Meurs et al., 2023; Yu et al., 2021).

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In this context, the present study aimed to analyse the offensive game patterns in Brazilian high-level men's volleyball, considering the opponent and the match location, whether played at home or away.

Our first hypothesis proposed that in home matches, eigenvector values would be higher for settings directed to position 3, with the middle attacker positioned in front of the setter against a single block, resulting in attack points, was partially confirmed. The results showed that the highest eigenvector values were observed for settings directed predominantly to positions 3 and 4, regardless of the opponent, with the middle attacker positioned in front of and close to the setter, leading to successful attacks. These findings align with previous research indicating that high-performance teams adopt a more conservative playing style, favouring sets to positions 2, 3, and 4, with a preference for playing in front of the setter (positions 3 and 4), utilizing the middle attacker in front of the setter (TF), and resulting in attack points (Conti et al., 2018; Rocha et al., 2022; Rocha, Laporta, Rodrigues, de Lira, et al., 2023). Although these data consistently illustrate team tendencies, some matches, particularly those involving the 1st and 2nd place teams, exhibited variations in setting locations, suggesting specific adaptations to the opponent's defensive system. In this regard, the literature indicates that considering game ecology, the interaction between the environment and the opponent facilitates adaptations in playing strategies, with new patterns emerging in response to environmental constraints (Araújo et al., 2006, 2017; Dutra et al., 2021; Woods et al., 2020). Conversely, in some matches played by the 2nd and 4th place teams, higher eigenvector values were observed for attack continuity, suggesting difficulties in modifying offensive patterns to overcome the defensive system. This finding implies that players demonstrated a lower ability to read the game context, possibly due to maintaining a consistent attacking approach regardless of the opponent (Nascimento, Laporta, Rocha, Lira, et al., 2023; Nascimento, Laporta, Pedrosa, et al., 2023; Nascimento, Laporta, Rocha, De Lira, et al., 2023).

Our second hypothesis, which suggested that in away matches, eigenvector values would be higher for sets directed to positions 4 and 2, with attacks against a double block resulting in points, was partially confirmed. The highest eigenvector values were observed for settings directed to zones 3 and 4. In zone 3, attacks occurred close to (TF) and far from the setter (T7) against single blocks and resulted in points. These findings indicate that teams preferred to play with speed, a strategy well established in the literature (Martins et al., 2021; Rocha et al., 2022; Rocha, Laporta, Rodrigues, Guimarães, et al., 2023). Additionally, the high eigenvector values for position 4 may indicate the adoption of conservative setting strategies (Nascimento, Laporta, Rocha, Lira, et al., 2023; Nascimento, Laporta, Pedrosa, et al., 2023; Nascimento, Laporta, Rocha, De Lira, et al., 2023), as well as the use of combination plays based on the movement of the middle blocker, the objective is to fixate the opposing middle blocker, making it more difficult for them to block the outside hitter (Nascimento, Laporta, Rocha, Lira, et al., 2023; Silva, Sattler, et al., 2016). In the analysed matches, this was characterized by the middle attacker jumping for an attack in front of and far from the setter while the position 4 attacker jumped to attack in zone 4, close to the middle attacker, a play known as the "*overball*." Another explanation for the high eigenvector values for position 4 is the possibility of attacking in the setter's blocking zone, resulting in a lower block reach and better attacking conditions (Silva et al., 2013; Silva, Sattler, et al., 2016). Overall, these findings suggest that the teams' game strategies remained unchanged despite match location, although extensive literature indicates that these variable influences performance and can lead to strategic adaptations (van Meurs et al., 2023; Yu et al., 2021).

Our third hypothesis, which stated that there would be differences in game patterns depending on the opposing team, was partially confirmed. We observed that the trends presented in hypotheses 1 and 2 were maintained in most matches, with sets directed in front of the setter against single or broken double blocks, resulting in a successful attack. However, there was variation in eigenvector values based on team rotation and set timing, indicating that specific rotations, depending on the match, allowed for better team

performance, as did particular moments within the set. These findings demonstrate that performance depends on the relationships that constitute game constraints, with team rotation influencing critical aspects of game dynamics (Đurković et al., 2008; López et al., 2023; Silva, Sattler, et al., 2016), such as serve-reception, setting-blocking, and attack-blocking interactions.

Although game patterns, considering variables such as middle-blocker attack location, setting distribution, number of blockers, and attack outcome, exhibited minor variations, suggesting stability in playing style regardless of the opponent, as previously described in the literature (do Nascimento et al., 2024; Nascimento, Laporta, Pedrosa, et al., 2023), it is possible that a team's rotation at the beginning of the set, depending on the opponent's rotation, could enhance performance, and this is due to the interplay of offensive and defensive aspects across the net, as team performance varies based on rotation (Silva et al., 2013; Silva, Sattler, et al., 2016). Furthermore, these rotational advantages may emerge in specific phases of the set, justifying the differences in eigenvector values across different set periods. In this context, a team's playing pattern is adjusted in response to the opponent's structure across the net, allowing higher-ranked teams to establish dominance over lower-ranked teams.

Although the results of this study indicate similarities between teams when playing at home and away, regardless of the opponent, it is important to emphasize that, in high-performance teams, even slight differences can significantly impact match outcomes (Laporta et al., 2015). On the other hand, it is also necessary to consider that teams recruit athletes based on a desired playing pattern, which tends to be maintained throughout the competitive season. While gameplay requires adaptations to the context, under pressure conditions, players often execute actions with which they are most familiar, which may explain the minor variations observed in this study. Additionally, it should be noted that coaches have a defined playing philosophy, and its implementation may shape the team's style of play, potentially restricting tactical adjustments. As a practical implication, we suggest that high-level teams be trained to adapt to game contexts beyond just the physical attributes of the athletes. In this regard, teams should develop a flexible tactical game plan that can be adjusted according to the opponent.

CONCLUSION

High-level Brazilian men's volleyball teams exhibit minimal variations in their playing style within the complex system, with finalist teams showing differences in the distribution and attack patterns of the middle-blocker. Additionally, it was observed that teams modified their initial positioning at the beginning of the set, with the setter adjusting their starting position. These findings suggest that minor adjustments, such as the team's initial formation and middle-blocker distribution, at the highest level of Brazilian volleyball, can significantly impact performance, ultimately distinguishing team outcomes.

AUTHOR CONTRIBUTIONS

All authors contributed significantly to the final version of this manuscript and to the interpretation of the results. Study design: MHN, LL, HU, and GDCTC. Data collection: MHN, ACRR, ABF. Statistical analysis: PHCV, MCJR, and CRC. Data interpretation: JSG, GFP, and GDCTC. Literature search: LL and HU. Writing - preparation of the original draft: CRC, ABF, and JSG. Writing - review and editing: all authors. Supervision: GDCTC. Project administration: GDCTC. All authors read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICS STATEMENT

The Federal University of Goiás Ethics Committee approved the study under protocol number CAAE: 15137319.6.0000.5083.

DATA AVAILABILITY STATEMENT

The supplementary material contains data supporting this study's conclusions. If the raw data need to be sent, the corresponding author should be contacted.

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ORIGINAL ARTICLE

The impact of video feedback on motor skill and motivation in acrobatic gymnastics through the use of digital tools in physical education

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ABSTRACT

This study investigates the effects of video feedback (VFB) on motor learning and motivation in acrobatic gymnastics (AG), a discipline demanding high levels of coordination and spatial awareness. Forty-two non-gymnasts (aged 11.59 ± 0.70y) were assigned to either an experimental group (VFB) or a control group (verbal feedback only) and participated in an 11-session AG program over 10 weeks. The learning task involved three acrobatic figures, Airplane, Square, and Reverse handstand, performed within a choreographed sequence. Motor performance was assessed using observation grids and joint angle analysis, while motivation was measured using the situational interest scale. Results showed significantly greater improvements in the VFB group for all three figures, both in performance scores (e.g., Reverse handstand: +247% vs. +38%) and joint angles (e.g., Aeroplane: +29% vs. +8%). Moreover, students receiving VFB reported higher motivation levels. These findings underscore the pedagogical value of VFB, suggesting it enhances both technical execution and student engagement more effectively than verbal feedback alone. VFB emerges as a promising digital tool to support motor learning and motivation in physical education, particularly in complex disciplines like AG.

Keywords: Performance analysis, Acrobatic gymnastics, Video feedback, Motor learning, Motivation, Physical education.

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INTRODUCTION

Researchers in motor learning and control study in depth the conditions of teaching and learning to identify optimal strategies for significant improvements in the acquisition of motor and cognitive skills (Souissi et al., 2024). One particularly effective strategy is the integration of new technologies into the teaching and learning process (Mödinger et al., 2022; Souissi et al., 2024). Indeed, the information and communication technology (ICT) has become a crucial tool in the development of the teaching approach, as it fosters innovation in the field of education. The introduction of ICT supported the learning tools such as smartphones, tablets and software, has led to a transformation in the classrooms (Dreimane & Upenieks, 2022). The integration of new technologies in the PE has helped to identify and improve the learners' performance and implement more effective interventions, which introduces a whole new way of engaging with physical activities and exercise learning (Saklani, 2023; Siekańska et al., 2021). In fact, in the PE context, providing effective feedback is essential for improving the student's motor skills and ensuring the learning quality (Han et al., 2022). According to Bhattacharyya et al. (2020), feedback plays a crucial role in the assessment process, with numerous studies highlighting its significant impact on learning outcomes. It is often regarded as "*the most powerful single moderator that enhances achievement*." Feedback provides personalized insights derived from direct observation, thoughtfully designed and communicated to help individuals maximize their potential. Building on existing literature, recent research has expanded our understanding of observational learning as a mechanism for enhancing motor skill acquisition (Nijmeijer et al., 2024). Among the available feedback methods, the ICT has found their role through the video feedback (VFB) method, which has emerged as a promising tool to support the learning in the PE (Potdevin et al., 2018; Schmidt & Wrisberg, 2008). In this context, several research studies report that sports pedagogists and physical educators have recently been compelled by technological advancements to reconsider methods of providing movement-related feedback and to experiment with new teaching tools, most of which are centred on the use of video feedback (Potdevin et al., 2018).

Most researcher agree that VFB is considered an essential strategy for guiding learners in making real (time adjustments during practice, thereby facilitating the development and refinement of new motor skills. When used as a formative assessment, it serves as an effective tool for both tracking performance development and providing instructional guidance. Formative feedback involves also assessing learning through data collection and specific analyses tailored to the student's level, followed by giving feedback to learners through verbal, written or visual means (Morris et al., 2021). Moreover, by engaging with VFB, learners can actively analyse their own performance, allowing them to identify strengths and areas for improvement. Indeed, through video feedback, learners focused on their performance abilities, which ambled a deeper understanding and improvement, particularly in complex motor tasks requiring coordination and power to successfully execute a skill (Nowels & Hewit, 2018; Zhou et al., 2021).

In addition, several studies have showed the effectiveness of VFB in acquiring a variety of sports skills within relatively short learning periods (Mödinger et al., 2022). This included gymnastics (Merian & Baumberger, 2007; Nowels & Hewit, 2018; Potdevin et al., 2018), front crawl in swimming (Kretschmann, 2017), soccer (Harvey & Gittins, 2014), hurdling (Palao et al., 2015), volleyball (Parsons & Alexander, 2012), and weightlifting (Rucci & Tomporowski, 2010; Souissi et al., 2023). While these studies have highlighted the effectiveness of VFB in motor learning, it should be noted that in several cases, depending on the learning context, studies have also demonstrated that combining VFB with attentional cues and verbal feedback is an especially effective pedagogical strategy for optimizing learning activities (Han et al., 2022; Potdevin et al., 2018). In terms of feedback forms, in most cases, both visual feedback and the combination of visual and

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verbal feedback have proven to be highly effective in significantly enhancing students' motor skill development (Han et al., 2022).

Moreover, to the best of our knowledge, there has been limited research investigating the effect of VFB on motor learning in acrobatic gymnastics (AG), a highly activity. This discipline encompasses various motor skills, including complex coordination and precise execution (Šalaj et al., 2019). Mastery of these skills requires careful attention to posture and aesthetic quality, especially when performing gymnastic exercises on the springboard and the floor. Additionally, previous research has affirmed that gymnastics significantly enhances physical attributes such as strength, endurance, and bone mineral density (Jorgic et al., 2011). Nevertheless, in a discipline closely related to AG, (Potdevin et al., 2018) explored the impact of VFB on skill acquisition in gymnastics during PE sessions. The study found that the use of VFB with reliable performance data encouraged novice learners to reflect on their practice, leading to improvements in their motor skill, self-assessment, and their motivation.

Added to the technical skills improvement, AG also impacts students' spatial awareness, self-esteem, and self-confidence (González-Valero et al., 2020), while simultaneously increasing their motivation and promoting their active participation (Ramirez-Granizo et al., 2020). A strong relationship has been demonstrated between the gymnastic performance, motivation and experience enjoyment in this context (Armada Martínez et al., 2021). To examine students' motivation and engagement in PE, researchers have primarily focused on personal motivational factors, often overlooking environmental influences. Addressing this gap, interest theory provides a framework for understanding how environmental and activity-specific content impact motivation. Situational Interest (SI) is defined as the temporary appeal of an activity to individuals in a specific context and at a particular moment (Kermarrec et al., 2014). According to (Romdhane & Khacharem, 2021), situational interest can be influenced by the design and use of instructional materials. In a PE context, SI is regarded as a multidimensional concept comprising five key dimensions: novelty, challenge, attention demand, exploration intention and immediate pleasure. Additionally, a sixth dimension, total interest, has been introduced, representing the overall appreciation of SI for a given situation (Roure et al., 2016). With this in mind, numerous studies in PE have explored the impact of technology integration on student learning, particularly in relation to motor and cognitive skills development.

From this perspective, VFB has been attributed significant attention from researchers. (Roure et al., 2019) showed that integrating technology-based learning tasks in PE, (such as the "*PE Badminton*" application on a tablet) positively influences the five dimensions of SI (novelty, challenge, attention demand, exploration intention, and immediate enjoyment) when compared to traditional learning tasks during a badminton lesson (Roure & Pasco, 2018). Similarly, Roure (2019), using the SI theory, highlighted that incorporating digital technologies, such as VFB paired with teacher traditional feedback, effectively enhances students' SI in PE, particularly in a gymnastics unit (Romdhane & Khacharem, 2021).

According to recent meta-analytic research, feedback generally promotes motor skill acquisition in PE settings regardless of task complexity (Han et al., 2022). However, the existing literature presents conflicting results about the relative effectiveness of various feedback modalities (e.g., verbal, visual, augmented) (Zhou et al., 2021). Although some research reports a greater impact of visual feedback over verbal feedback, others have failed to show statistically significant differences between modalities (Mödinger et al., 2022). Such discrepancies may be due to a variety of moderating factors, including the nature of the motor tasks, their inherent difficulty, the learners' proficiency levels, and other contextual variables. Consequently, to resolve these ambiguities further research focusing specifically on the application of VFB in complex, spatially

demanding exercises like AG seems necessary, both to clarify these ambiguities and to optimize teaching practices in PE.

From this perspective to the best of our knowledge, there are no effective interventions utilizing VFB in physical education that expressly target AG, despite its acknowledged promise. AG provides an interesting context for researching the impacts of VFB due to its inherent interpersonal coordination requirements, aesthetic criteria and spatial complexity. Unlike many previous studies on VFB, which focus on individual, linear movements, AG requires synchronized dyadic performance, precise postural control and frequent spatial reorientation, all aspects for which VFB is particularly important. Furthermore, using VFB with young novice AG learners could enhance their technical accuracy and self-assessment through accessible visual representations of their performance. These distinctive features highlight the pedagogical significance of VFB, as do the motivational challenges associated with the novelty and difficulty of AG in the context of PE. Therefore, the main objective of this study is to evaluate the impact of a VF intervention on the acquisition of motor skills and motivation when learning AG choreography in PE in young.

METHODS

Experimental design

The study employed a randomized, single-blind, controlled trial with repeated measures, involving two groups of non-gymnast novices with similar skill level, both instructed by the same teacher. An experimental group (EG) took part in a learning program using the video feedback system to self-correct. The VFB enables subjects to observe their actions in real-time and compare them either to a reference model or to their own prior performances. Learners have control over the displayed visual content. They were able to pause, fast-forward or rewind the video feedback. A control group (CG) received only verbal feedback and viewed static figures presented. Both groups followed a learning cycle of 11 AG sessions, including 9 learning sessions and 2 evaluation sessions, spread over 10 weeks. At the end of the cycle, participants were asked to perform three acrobatic figures in pairs in a choreographed sequence: Aero plane, Square and Reverse handstand. Acrobatic gymnastics training sessions were divided into initial and advanced sessions. the pretest was in the first session and the post-testing choregraphic sequences were at the 11th session.

Participants

A preliminary power analysis was calculated with G*Power software [version 3.1, University of Düsseldorf, Germany (Faul et al., 2009)] with a type I error of .05 and statistical power of 80%. The analysis showed that a minimum of 42 participants (e.g. divided into two groups) is sufficient to observe a significant and large effect size (d = 0.925) with a critical t = 2.024. Thus, the study sample of forty-five potential participants was initially considered for the study, three were excluded for not meeting the required conditions. Finally, 42 students (19 boys and 23 girls) were divided into two groups (Figure 1), an EG with (10 girls - 11 boys, 11.59 ± 0.70 years) and a CG with (13 girls - 8 boys, 12.20 ± 0.78 years). All participants were in good health and did not suffer from any disability, musculoarticular, cardiac, neurological or respiratory disease or dysfunction. Exclusion criteria were as follows: (a) refusal by the child to participate, (b) lack of parental consent, (c) any physical problem that temporarily or permanently prevented the student from performing the motor tests, and (d) beginners in AG with no specific previous knowledge. In addition, all participants and their parents were informed in advance about the experiment and signed an informed consent form. The study was also conducted in accordance with the Declaration of Helsinki. This protocol was approved by the local research ethics committee (0107/2023; UR18JS01).

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Procedures

Both the EG and CG groups were invited to take part in a nine-session learning module in AG, with the aim of performing a choreography composed of three pairs of acrobatic figures. The figures 2, 3 and 4 show a detailed technical breakdown of the choreography. A professional teacher in AG defined all the criteria as well as technical errors correction during the choreography motor skill sessions. All of the currently available international gymnastics federation scoring code materials were used. The study's flow diagram is shown in Figure 1.

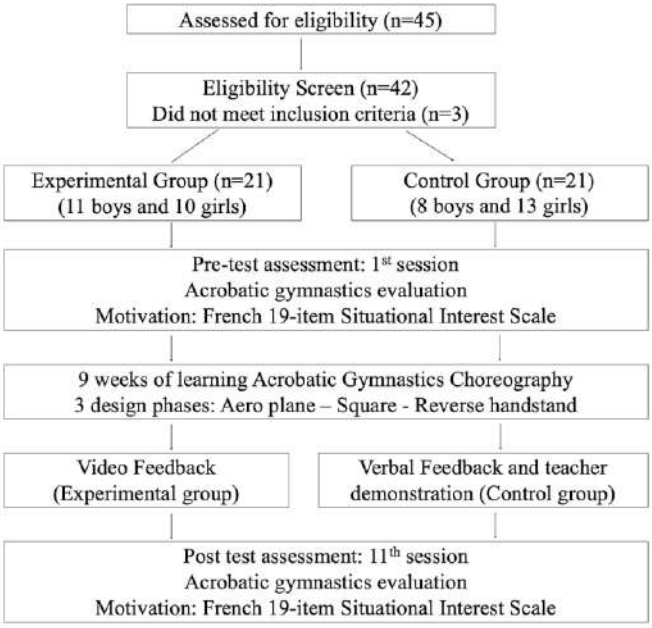

Figure 1. Flow diagram of the study.

Aero plane

The Aero plane is a static acrobatic duet figure consisting of three separate phases (Figure 2). In the setup phase (Figure 2A), the first student, acting as the carrier, lies on their back and positions their feet on the pelvis of the second student, the aerialist, who stands in front. The aerialist feels the carrier's hands while the carrier gently bends their legs. Once the aerialist's weight is fully supported by the carrier's feet, the carrier extends their legs, allowing the aerialist to achieve a stable, airplane-like position for 2 to 3 seconds during the maintenance phase (Figure 2B). In the stability phase, the carrier may hold the aerialist's shoulders for additional balance. Finally, in the dismount phase (Figure 2C), the aerialist tilts backward to descend safely. A common variation involves the aerialist extending their arms outward to maintain balance while remaining supported by the carrier's feet.

Figure 2. Aero plane design phases.

Square

Figure 3 describes the different phases of square. Firstly, the vaulted lies on the floor with their arms stretched towards the ceiling. The acrobat positions their ankles on the carrier's hands while simultaneously placing their hands on the carrier's ankles (Figure 3A). Next, the wearer straightens their upper body as the acrobat lifts their hips upwards in a synchronized movement. In the holding phase, both students create a square-like formation with their bodies and maintain the position for 2 seconds (Figure 3B). Finally, the last dismount phase consists of returning to the initial position and then pivoting to the side.

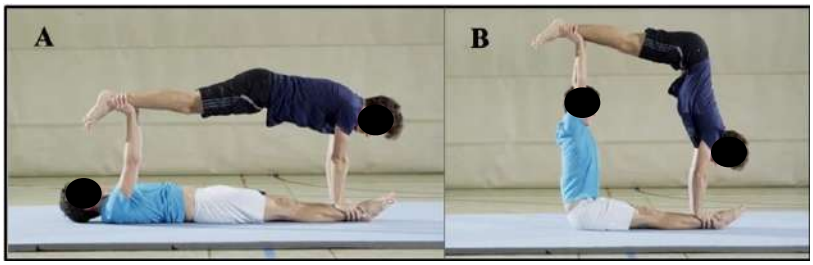

Figure 3. Square design phases.

Reverse handstand

The Reverse handstand (Figure 4) represents the third figure in the choreography and consist of two separate phases. The set-up phase (Figure 4A, B and C): the acrobat transitions into an inverted handstand, positioning themselves against the back of the carrier. The carrier firmly grasps the lower part of the acrobat's legs and gradually lowers their body until their glutes align perfectly with the aerialist's shoulder blades. While the acrobat maintains the arched position, the carrier tilts forward, keeping the back solid. The dismount phase (Figure 4D): the carrier raises their hips so as to place the acrobat on the ground in front of him. It is crucial that the carrier bends forward and round their back to effectively support the acrobat's shoulder blades at hip level while in the inverted position. The flyer executes a bridge movement over the carrier, facilitating hip elevation. For optimal execution, the carrier must maximally close the trunk lower limb angle to ensure a controlled and stable descent.

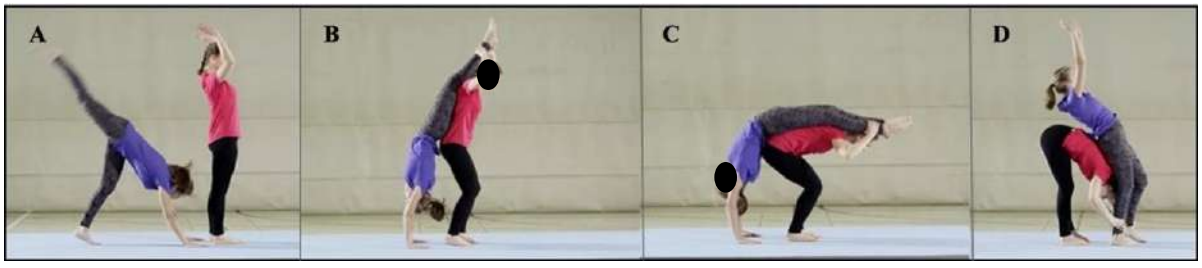

Figure 4. Reverse handstand design phases.

Assessments

Anthropometric variables

The mean measures of participants were as follows: age: 11.59 ± 0.70 years, stature 146.05 ± 2.52 cm, Body mass 37.10 ± 2.20 kg / BMI: 17.35 ± 1.23 kg/m^2. As required by the International Society for the Advancement of Kinanthropometry (ISAK), the ISAK guidelines were used for all assessments (Scafoglieri et al., 2012). Body weight was measured using a digital scale (Seca 769, Germany; accuracy 0.1 kg) and height was taken using a stadiometer (Seca 220, Germany; accuracy 0.1 cm). Each participant's body mass

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index (BMI) was measured by a bioelectrical impedancemeter (TBF-300, Tanita, Tokyo, Japan) for each participant.

The video feedback device

The VFB system was implemented for the experimental group using a standardized video recording setup. Two SONY FDR-AX43A/4K digital cameras were used to capture video footage, adhering to a standardized protocol. One camera was fixed on a tripod at a height of 1.50 meters and placed 3 meters away from the gymnasts to ensure uniform and reproducible recordings. The recorded video sequences were analysed using Kinovea software (version 2023-1.2) to assess movements performance. This methodological approach is consistent with protocols adopted in previous research (Souissi et al., 2021).

Special individual assessment sheet

During the testing sessions, no feedback or corrections were provided to the learners. The recorded sequences of acrobatic figures were analysed by two AG experts (recognized as judges by the International Gymnastics Federation (FIG)) using assessment grids based on the success criteria outlined in the FIG Code of Points. Each acrobatic movement, Aero plane, Reversed handstand and Square, was analysed according to qualitative criteria (technical skills according to a two-level appreciation scale, (*i*) unsuccessful execution (-) and (*ii*) successful execution (+)) as well as a quantitative criterion, measurement angle. According to (Favre, 2017) the quantitative data were converted into scores, where negative evaluation corresponded to 0 points, and a positive evaluation corresponded to 1 point. As illustrated in Figure 5, the key angles (Y° = 90° (Figure 5A); X° = 90° (Figure 5B); α° = 45° (Figure 5C)) served as reference metrics for analysing skill development throughout the intervention.

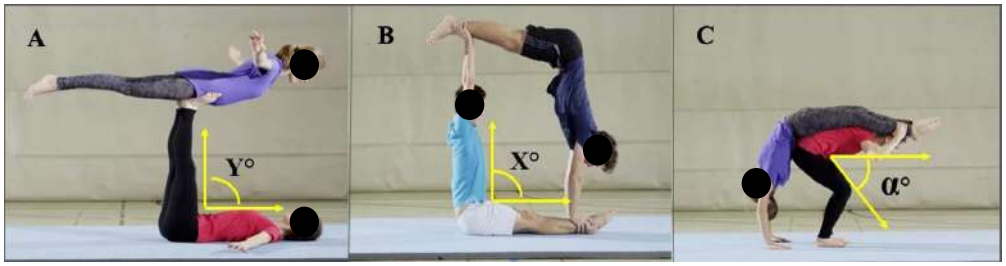

Figure 5. Angles measurement.

Motivation

The Situational Interest Scale with French validation (EMIS-EP) (Roure et al., 2016), was implemented to assess intrinsic motivation levels among students across all groups. This instrument comprises six dimensions: *(1)* instant enjoyment, *(2)* exploration intention, *(3)* novelty, (4) attention demand, (5) challenge and *(6)* total interest). Participants rated each item on a five-point scale, ranging from 1 (strongly disagree) to 5 (strongly agree).

Statistical analysis

All data are reported as mean ± standard deviation (SD). Data analysis was carried out using SPSS 25.0 statistical software (SPSS 20.0 for Windows, SPSS Inc., Chicago, IL, USA). The Shapiro-Wilk test was applied to verify data normality. The independent-samples t-test was used to assess differences in youth anthropometric variables. A two-way mixed analysis of variance (ANOVA; 2 groups [CG, EG] × 2 test times [pre- and post-test]) with repeated measures was performed to analyse variations over time. The t-test for independent samples was employed to compare technical scores, angles keys indexes, and motivation

between the EG and CG. A two-factor repeated measures of analysis of variance (ANOVA) was conducted to evaluate group × time effect across all variables. When a significant group × time interaction was detected, the Bonferroni post-hoc test was applied to determine intragroup differences (pre- vs. post-test). Effect sizes were calculated as partial eta-squared η_p^2 for ANOVA ($\eta_p^2 \geq 0.01$, small effect size; $\eta_p^2 \geq 0.06$, medium effect size; $\eta_p^2 \geq 0.14$, large effect size), and as Cohen's d for t-test ($d \geq 0.2$, small effect size; $d \geq 0.5$, medium effect size; $d \geq 0.8$, large effect size). The significance level was fixed at $p < .05$.

RESULTS

Anthropometric measurements

As shown in Table 1, the anthropometric measurements were designed to define the initial level of fitness of the participants and therefore the formation of homogeneous groups with an approximately similar level of fitness to guarantee the experiment's validity. According to the results of the mixed ANOVA test, there were no significant interactions between the two groups ($p > .05$).

Table 1. Anthropometric characteristics of the sample (n = 42).

Indicator	Group	(Mean ± SD)	*p*-value
Age (years)	EG (n = 21)	11.59 ± 0.70	.896
	CG (n = 21)	12.02 ± 0.78	
Height (cm)	EG (n = 21)	158.5 ± 2.01	.123
	CG (n = 21)	153.6 ± 3.10	
Body weight (kg)	EG (n = 21)	50.89 ± 2.98	.470
	CG (n = 21)	55.32 ± 1.42	
BMI (kg/m^2)	EG (n = 21)	20.17 ± 1.24	.390
	CG (n = 21)	19.24 ± 1.22	

Note: SD: Standard deviation. BMI: body mass index. EG: experimental group. CG: control group. p-value: significant value.

Technical performance score

Regarding the score performance of the three choreography sequences, the repeated-measures ANOVA revealed a significant Group × Time interaction effect, as shown in Table 2. No significant baseline differences were observed between both groups (EG and CG) in the pre-test, confirming the homogeneity of both groups before the intervention. A significant overall improvement in performance was observed in the EG compared to the CG. The Reserve handstand had the higher impact ($F = 19.42$; $p < .001$; ES = 0.493) indicating a large effect size. This was followed by Square ($F = 6.36$; $p = .02$; ES = 0.242) and Aero plane ($F = 6.14$; $p = .022$; ES = 0.235), both showing moderate effect size.

Post hoc analysis using paired *t*-test further confirmed a significant improvement of the chorography performance following VFB intervention in the EG. The percentage improvement was higher for the Reverse handstand (247%; $t = -6.375$; $p < .000$), followed by Aero plane (176%; $t = -5.36$; $p < .000$) and Square (77%; $t = -4.79$; $p < .001$). However, the CG exhibited more moderate improvement, with only Aero plane showing a significant improvement (74%; $t = -2.47$; $p < .033$), while the improvement for Square (12%; $t = -0.476$; $p = .645$) and Reverse handstand (38%; $t = -1.93$; $p = .082$) were not statistically significant.

Following the VFB intervention, the post-test between-group comparison confirmed that the EG outperformed the CG across all three choreography sequences, with significant differences observed for Aero plane ($t = 3.33$; $p = .003$); Square ($t = 3.402$; $p = .004$) and the Reverse handstand ($t = 5.33$; $p < .000$). These findings suggest that the VFB intervention had a significant impact on motor learning outcomes, particularly for more

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complex acrobatic movements. It seems clear that the larger improvement observed in the EG highlight the potential of VFB in enhancing self-perception and technical performance AG.

Table 2. Effect of acrobatic gymnastic method on chorography performance in a pre- and post-test (n = 42).

Acrobatic figures	**EG (n = 21)**			**CG (n = 21)**		
	Pre	Post	Δ%	Pre	Post	Δ%
Aeroplane	1.45 ± 1.03	4.00 ± 0.77	176	1.36 ± 0.92	2.36 ± 1.43	74
Square	2.09 ± 1.37	4.18 ± 0.75	77	2.18 ± 1.25	2.45 ± 1.50	12
Reverse handstand	1.18 ± 0.98	4.09 ± 0.83	247	1.45 ± 1.03	2.0 ± 1.00	38
Acrobatic figures	**ANOVA Group**			**ANOVA (Group × Time)**		
	F	*p-value*	ES	F	*p-value*	ES
Aeroplane	6.710	.017	0.251	6.149	.022	0.235
Square	4.280	.052	0.176	6.360	.020	0.242
Reverse handstand	8.475	.009	0.298	19.420	.000	0.493

Note: Δ: percentage difference; (F) Test value; (p) significant value; ES = effect size.

Performance key angles

The analysis of effect of VFB is based on a repeated-measures ANOVA, including the effects of time and the interaction group × time. No significant baseline differences were observed between both groups.

The results of the statistical analyses using ANOVA presented in Table 3 showed a group time interaction for the three angles measured, indicating a significant overall progression in the EG compared to the CG. The strongest effect is observed for Aero plane ($F = 53.39$; $p < .001$; ES = 0.72), followed by Reserve handstand ($F = 21.77$; $p < .001$; ES = 0.52) and Square ($F = 6.72$; $p < .05$; ES = 0.25).

Table 3. Effect of acrobatic gymnastic method on key angles performance in a pre- and post-test.

Angle	**EG (n = 11)**			**CG (n = 11)**		
	Pre	Post	Δ%	Pre	Post	Δ%
(Y°) Aero plane	64 ± 3.28	82.73 ± 4.22	29	66.09 ± 4.06	71.55 ± 2.38	8
(X°) Square	118 ± 7.71	94.00 ± 3.19	-20	111 ± 10.50	97.82 ± 6.24	-12
(α°) Reverse handstand	34.55 ± 4.41	45.45 ± 2.20	31	32.00 ± 3.22	36.73 ± 3.84	15
Angle	**ANOVA Group**			**ANOVA (Group × Time)**		
	F	*p-value*	ES	F	*p-value*	ES
(Y°) Aero plane	13.92	.001	0.411	53.39	.000	0.728
(X°) Square	0.288	.597	0.014	6.72	.017	0.252
(α°) Reverse handstand	17.51	.000	0.467	21.77	.000	0.521

Note: Δ: percentage difference; (F) Test value; (p) significant value; ES = effect size.

A post hoc analysis showed a significant improvement of the angle measurements after VFB intervention for the EG, respectively: Aero plane 29% ($t = -14.09$; $p < .001$); Square -20% ($t = 14.42$; $p < .001$) and Reverse handstand 31% ($t = -8.91$; $p < .001$). However, more moderate improvement was observed in the CG, respectively: Aero plane 8% ($t = -4.4$; $p < .001$); Square -12% ($t = 3.84$; $p < .003$) and Reverse handstand 15% ($t = -9.33$; $p < .000$).

For the post-test, conducted after VFB intervention, the independent t-test results showed a significant improvement in the EG for both the airplane angles ($t = 7.65$; $p < .001$) and the Reverse handstand ($t = 6.52$; $p < .001$). However, no significant difference was found between groups for the Square angle ($t = -1.8.84$; $p = .086$) suggesting that both groups benefited similarly for this specific skill. Effect sizes support these results,

with large effects observed for Aero plane (ES = 0.728) and Reverse handstand (ES = 0.52) and a small to moderate effect for the Square angle (ES = 0.25).

Motivation effects

A Kruskal-Wallis was conducted to examine differences in situational interest between the EG and the CG before and after the intervention. As illustrated in Table 4, prior to the acrobatics choreography intervention, no significant differences were found between the two groups across any of the six dimensions of the EMIS-EP scale ($p > .05$). These findings indicate that both groups were homogeneous in terms of intrinsic motivation before the intervention. Following the intervention, significant differences emerged in four dimensions. (i) the evolution of instant enjoyment: the EG exhibited a higher mean rank (25.71) compared to the CG (17.29), resulting in a significant difference ($\chi^2 = 5.518$, $p = .019$). (ii) exploratory intent: the EG demonstrated a higher mean rank (25.93) than the CG (17.07), with a statistically significant difference ($\chi^2 = 5.57$, $p = .018$). (iii) novelty: the post-test scores were significantly higher for the EG (mean rank = 29.95) compared to the CG (mean rank = 13.05), with a highly significant effect ($\chi^2 = 20.586$, $p = .001$). (iv) total interest: the EG demonstrated greater overall interest (mean rank = 26.31) compared to the CG (mean rank = 16.21), with a statistically significant difference ($\chi^2 = 7.983$, $p = .005$). In contrast, no significant post intervention differences were observed for attention demand ($p = .072$) or challenge ($p = .39$).

Table 4. Pre-post-test comparative intrinsic motivation analysis between acrobatic gymnastics groups (n = 42).

Intrinsic motivation variable	**Group**	**Pre-Post Intrinsic motivation index**					
		Mean rank		χ^2		Sig (*p*-value <.05)	
		Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Instant enjoyment	EG (n = 21)	22.62	25.71	0.365	5.518	.546	.019
	CG (n = 21)	20.38	17.29				
Exploratory intention	EG (n = 21)	22.43	25.93	0.258	5.579	.612	.018
	CG (n = 21)	20.57	17.07				
Novelty	EG (n = 21)	22.76	29.95	0.471	20.586	.493	.000
	CG (n = 21)	20.24	13.05				
Attention demand	EG (n = 21)	21.24	24.86	0.020	3.236	.889	.072
	CG (n = 21)	21.76	18.14				
Challenge	EG (n = 21)	20.14	23.07	0.537	0.739	.464	.390
	CG (n = 21)	22.86	19.93				
Total interest	EG (n = 21)	24.31	26.79	2.243	7.983	.134	.005
	CG (n = 21)	18.69	16.21				

These findings indicate that VFB learning strategies in AG positively influenced students' instant pleasure for learning, exploratory behaviour, perception of novelty and overall situational interest.

DISCUSSION

This study investigated the effects of using VFB approach as pedagogic tool on motor skill acquisition, and motivation in acrobatic gymnastics choreography during PE sessions. Acrobatic gymnastics offers a unique context for VFB due to its interpersonal coordination, aesthetic precision, and spatial complexity, making it particularly effective for enhancing motor learning and motivation in novice learners (Ávalos et al., 2020). In terms of technical performance, initial results confirmed that the anthropometric characteristics of both groups were similar. Aligning with previous studies (Thomas & Thomas, 1988) as well as those of (Palao et al., 2015), these factors do not significantly influence the outcomes of skill acquisition of the same age and skill level of the children.

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Overall, the results showed a significant improvement in motor skills within the experimental group compared to the control group between the pre-test (prior to the intervention) and the post-test (after the intervention). This development was noticeable both in the technical performance scores for the execution of the three acrobatic movements and in the evolution of the joint angles measured for each movement. Importantly, the analysis of the pre-test data revealed no significant differences between the groups, confirming an initial homogeneity in skill levels, characterized as beginner. Statistical analysis further revealed a significant group × time interaction effect, indicating that the improvements observed in the experimental group. These findings highlight the effectiveness of VFB as a relevant didactic tool for enhancing motor learning. Consistent with the literature, feedback is recognized as a critical factor in facilitating the development of motor skills (Mödinger et al., 2022; Wulf et al., 2010), and serves as a key mechanism for exploring performance abilities (Han et al., 2022). In this regard, PE students require accurate and practical information to learn motor skills effectively and to identify and address their specific learning needs, as emphasized by (Schmidt & Lee, 2011).

Regarding technical performance outcomes, the improvements observed in the experimental group across the three figures, *Aeroplane* (176%), *Square* (77%) and *Reverse Handstand* (247%), were considerably greater than those recorded in the control group (74%, 12%, and 38%, respectively). These results indicate that VFB not only enhanced the quality of movement execution but also strengthened technical skill acquisition more efficiently than verbal feedback alone.

These findings support the idea that fixing motor skill mistakes is closely dependent on the learning strategy used, as highlighted by (Milanese et al., 2017). Thus, the use of VFB likely facilitated motor errors detection and adjustment, promoting a process of self-regulation and a deeper understanding of the success criteria for acrobatic figures. Consequently, VFB appears to be an effective pedagogical tool for optimizing motor skill learning. These findings are consistent with the research carried out by Merian and Baumberger (2007), as well as (Mödinger et al., 2022), who stated that by offering students an opportunity of seeing and reviewing the movement performed, mistakes can be analysed and remedied by applying appropriate adjustments. Thus, the impacts of learning new complex gymnastics element depend on the type of feedback provided.

Furthermore, the statistical analysis of joint angle evolution for each acrobatic figure revealed that the experimental group exhibited a greater ability to interpret and integrate the augmented information provided by VFB. This enhanced their postural awareness during the learning sessions and ultimately led to significant and measurable improvements in postural control. Although both groups (experimental and control) showed improvements across the three acrobatic figures, highlighting the positive effect of feedback on motor learning regardless of its nature (Han et al., 2022), the experimental group demonstrated significantly greater progress, particularly for the Aeroplane (29 vs. 8%) and Reverse handstand (31 vs. 15%) figures compared to the control group. However, for the Square figure, no significant difference was observed between the two groups, although the improvement recorded in the experimental group (-20%) remained superior to that of the control group (-12%). This finding may be explained by the lower complexity of the Square figure, which appears to demand less coordination, synchronization, and spatial complexity than the other two figures. These results underline the crucial role of verbal feedback (Kernodle et al., 2001; Starzak et al., 2022) and confirm the effectiveness of VFB in optimizing motor learning (Nowels & Hewit, 2018; Palao et al., 2015; Potdevin et al., 2018).

These results are consistent with previous studies that have demonstrated the positive impact of VFB on the learning of complex technical movements (Merian & Baumberger, 2007; Souissi et al., 2021). Additionally, they demonstrate the potential of VFB learning procedures to facilitate the acquisition and improvement of students' AG skills within a limited instructional timeframe. Similar effects have been observed in previous

studies in other sport specialties, including gymnastics (Potdevin et al., 2018), front crawl swimming (Kretschmann, 2017), hurdling (Palao et al., 2015), and weightlifting (Souissi et al., 2023). These studies suggest that integrating VFB into PE teaching can serve as a powerful tool for accelerating the acquisition of technical skills and optimizing learning efficiency across a wide range of motor tasks in relatively short teaching periods, as demonstrated in the present study.

Magill and Anderson (2013) emphasized the importance of VFB in strengthening procedural memory. Their work demonstrated that VFB assists learners in developing robust and flexible motor schemas, thereby enhancing motor skill retention. They further suggested that the use of technological aids such as VFB can be effectively integrated across various educational contexts. Similarly, as highlighted by (Rè, 2017), different types of feedback contribute to motor development, suggesting that the integration of video represents an innovative approach within PE. While numerous studies have confirmed the effectiveness of VFB in motor skill acquisition, it is important to note, as Starzak et al. (2022) argue, that the role of feedback in the teaching-learning process for motor skills of varying complexity and difficulty levels has not yet been categorically established. Therefore, further research is necessary to better understand the efficacy of feedback, particularly in disciplines closely related to gymnastics.

In terms of motivational profile, the findings indicate that the development of motivation, exploratory intent, innovation, and overall interest within the experimental group significantly enhances students' intrinsic enjoyment. This intrinsic enjoyment, in turn, exerts a substantial positive effect on their performance. Furthermore, the integration of the innovative learning module and digital interventions notably contribute to an increase in students' motivation, reinforcing their engagement and fostering improved outcomes in the learning process. From a statistically point of view, this study confirms that VFB interactions fostered a motivational climate among students during AG classes in PE. Notably, both groups exhibited a significant change in motivation between the first and last AG sessions. Effectively, feedback experiences involving video technology perceived both interesting and motivating, leading to increase the improvements in instant enjoyment, exploration intention, innovation and overall interest. However, instant pleasure provides learner an immediate sense of positive satisfaction (Chen et al., 2014). It is noteworthy that the experimental group exhibited significantly higher scores in terms of instant enjoyment and exploratory intent compared to the control group. According to Roure and Pasco (2018) these two dimensions are particularly interesting because they are among the most potent variables in fostering students' interest development. Similarly, Potdevin et al. (2018) reported that VFB, had a more substantial impact on students' emotional responses in PE classes. Although both groups showed increased levels of enjoyment, the experimental group displayed a more pronounced enhancement, suggesting that the VFB may contribute to a heightened sense of engagement and satisfaction during the learning process. Learning a new skill combined with VFB increased students' engagement in their learning process, continuous readjustment of their skill development, self-assessment of task performance and collaboration with the PE teachers in the acquisition process. Though VFB is time-consuming, this digital device helps in achieving an optimal performance and enriching the learning experience of athletes.

At the statistical level, contrary to previous works, the current studies used mixed-method approach. Quantitative approaches were used to examine the potential value of VFB on students' motor skill improvement and motivation in a PE context. Moreover, to assess students' progress in motor skills learning, the acrobatic figures in pairs were digitally video-recorded and measured the attempts were calculated for each student in each session. All acrobatic movements were analysed using qualitative criteria for technical skills and a quantitative criterion for the angle measurement.

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The most important limitation of this study was the time required for students to become familiar with the digital equipment used for VFB. A future study could focus on the use of VFB coupled with time-effect. Additionally, future pedagogical challenges should focus on developing PE quality of knowledge and professional skills related to the use and exploitation of digital tools by experimenting with new strategies would also help in the learning process.

Practical applications

The study highlights the significant impact of VFB in improving teaching and learning outcomes in practical physical education settings, particularly within acrobatic gymnastic. Through an analysis of students' performance and motivation, the findings suggest that VFB serves as a more effective and engaging method compared to traditional teaching techniques. Importantly, the results highlight VFB' potential as both a pedagogical and training tool that can foster increased student engagement, intrinsic motivation and motor skill acquisition. Furthermore, these outcomes suggest that VFB can be a valuable resource for physical educators, coaches and sports trainers, providing a scalable strategy for optimizing technical learning and performance in AG.

AUTHOR CONTRIBUTIONS

Mohamed Sami Bouzid: research concept and study design, literature review, data analysis and interpretation, statistical analyses. Hassan Melki: literature review, data analysis and interpretation, statistical analyses. Montassar Ben Romdhane: literature review, writing of the manuscript. Wissal Khalfallah: research concept and study design, literature review, data collection. Youssef Rezgani: research concept and study design, data collection, analysis and interpretation. Sabra Hammoudi, Ghazi Racil and Johnny Padulo: writing – review and editing, supervision.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

PATIENT CONSENT STATEMENT

Written informed consent was obtained from all study participants parents.

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ORIGINAL ARTICLE

A comparison of three-point shooting effectiveness in the Euroleague and NCAA DI basketball

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ABSTRACT

Shooting is a fundamental basketball skill that critically influences game outcomes. The purpose of the present study was to compare the effectiveness of three-point shooting between the Euroleague and NCAA Division I during the 2020-21 season, evaluating factors such as shooting accuracy, player position, type of offense, and timing of shot execution. The analysis was based on the recording of 3,249 shots from 70 games. Results demonstrated higher shooting percentages in the Euroleague (38.4%) compared to the NCAA (35.1%). Differences were observed in the type of offense, with the NCAA exhibiting a higher proportion of fast-break (transition) plays, whereas the Euroleague primarily focuses on organized set plays. Shot execution timing emerged as the most significant differentiating factor between the two leagues. Player position also influenced effectiveness, with guards being the primary shooters, however, forwards in the Euroleague demonstrated higher efficiency compared to their NCAA counterparts. CHAID analysis confirmed the importance of shot timing, player position, and shooting effectiveness as critical discriminant factors, highlighting the Euroleague's tendency towards more patient and tactically organized offenses in contrast to the faster and more intense style of play in the NCAA. These findings provide valuable insights for analysts and coaches to develop effective offensive tactics tailored to the specific characteristics of each competition.

Keywords: Performance analysis, Basketball, Euroleague, NCAA DI, Three-point shooting, Effectiveness, Players position.

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INTRODUCTION

The importance of shooting in basketball has been a subject of study for analysts for many decades. A significant number of coaches assert that shooting is the most critical, enjoyable, and valuable fundamental skill in basketball, as it largely determines the score and outcome of the game (Gomez et al., 2008; Sampaio et al., 2015). Some coaches argue that scoring is more likely from close range, whereas long-distance shots should never be attempted unless all possibilities to get the ball under the basket have been exhausted (Erčulj et al., 2015). Gjøen et al. (2023) also supported in their study that, given the higher field goal percentage of two-point shots, in some situations players may prefer to attempt two-pointers instead of three-pointers, even though the latter yield more points. When this option is unavailable due to intense defensive pressure, athletes then opt for mid-range or even longer distance shots, particularly three-pointers (O'Donoghue, 2009; Kilcoyne, 2020). According to two recent studies analysing data from Euroleague games and corresponding national leagues (Mikołajec et al., 2021; Plakias et al., 2024), the Effective Field Goal Percentage (eFG%), which incorporates three-point shooting performance, has emerged as one of the most important performance indicators predicting game outcomes. Teams with higher three-point efficiency were found to have significantly increased chances of winning. This factor is critical for the observed increase in long-range shot attempts and corresponding shooting percentages seen over recent decades in the Euroleague (Musin et al., 2020; Foteinakis & Pavlidou, 2024a).

The significance of the three-point shot is further highlighted by its strong correlation with winning outcomes in both NCAA Division I and the NBA (Zajac et al., 2023). Since the establishment of the three-point line in the NCAA in 1987, there has been a substantial increase in attempts (attributable to the numerical advantage of three-pointers over two-pointers), although this has not necessarily translated into increased scoring or offensive efficiency. An excessive emphasis on the three-point shot may prove misguided when undertaken regardless of player ability or at inappropriate moments (Stefani, 2023). Nevertheless, considerable weight should be placed on long-range shooting when a team possesses exceptional three-point shooters or in late-game situations when a team is trailing on the scoreboard (Gou et al., 2022).

Generally, Euroleague players tend to be older with extensive experience either from national leagues or the NBA, compared to NCAA players who are younger and lack professional experience. Significant differences in league regulations also exist (e.g., 30-second shot clock, bonus rules), alongside differences in game structure and style (such as spacing, pick-and-rolls, and tactics) compared to the NCAA, which is significantly influenced by coaching strategies that limit players' freedom of decision-making (Fotinakis et al., 2002; Mandic et al., 2019; Paulauskas et al., 2024; Foteinakis & Pavlidou, 2025).

Three-point shots at the end of games can be decisive, particularly in close contests involving professional players, such as in the Euroleague. The precision leading to effective shooting does not appear to be affected by fatigue (Slawinski et al., 2018). Physical fatigue induced during games does not alter the kinematic variables of the three-point shot in elite basketball players. However, during a game, the complex interaction of fatigue, tactical decisions, score, remaining time, and defensive pressure may affect both the kinematics and accuracy of three-point shots, especially in younger players (Malarranha et al., 2013). Csataljay et al. (2013) demonstrated that winning teams achieved higher three-point shooting efficiency as a result of greater tactical cohesion among teammates. The most significant difference between winning and losing teams was that winners could capitalize on opportunities and score more effectively, not only under no defensive pressure but also in the most challenging situations involving high defensive pressure. According to Zhang et al. (2023), factors such as coordination, balance, and core strength can influence the kinematics and accuracy of long-distance shots.

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In modern basketball, offensive plays are executed in three primary forms: transition situations (including fast breaks and early options), organized plays such as set plays, and a third category encompassing various other plays when the former two types are not applied, for example, second-chance plays following offensive rebounds (Selmanovic et al., 2015; Selmanovic et al., 2019). Research on the effectiveness of shots following offensive rebounds has shown that shooting accuracy increases by 67% compared to first-phase attempts. Winning teams were observed to be more effective than losing teams in scoring following offensive rebounds, which was attributed to better shot decision-making relative to their opponents (Cadenas & Ibanez, 2017; Stamiris et al., 2022). Teams that excel at offensive rebounding can significantly impact the game by converting missed shots into second-chance opportunities (Foteinakis et al., 2024).

The rapid expansion of performance analysis in basketball has led to the production of significant literature examining technical and tactical characteristics as well as efficiency indicators of players and teams across various competitions-leagues. However, literature systematically comparing the Euroleague and NCAA Division I remains extremely limited. This gap represents a significant research need, especially in areas related to decision-making, offensive tactics, and the timing of executions, such as three-point shooting. The purpose of the present study was to investigate potential differences in three-point shot execution in the Euroleague and NCAA Division I during the 2020-21 season, concerning variables such as effectiveness, type of offensive execution, timing of shot, player position, and the game period during which the shot occurred.

MATERIAL AND METHODS

Participants

The sample of the study consisted of 70 games from the Euroleague Championship (n = 35) and the NCAA Division I men's college basketball championship (n = 35). A total of 3,249 three-point shot sequences were recorded (Euroleague n = 1,774; NCAA Division I n = 1,475) during the 2020–2021 regular season. The selection of the championships was based on the highly competitive level of the participating teams, while the specific games were randomly selected from a predefined pool of games. Since this was an observational study conducted in a naturalistic setting without any experimental intervention, and all data were obtained from publicly available sources, obtaining informed consent from the athletes was not required (American Psychological Association, 1992).

Procedures

Initially, the game videos were recorded in MP4 format using a laptop with the Windows 10 operating system. Subsequently, the videos were imported into the SportScout STA software, where an analysis scheme was created based on the examined data. The coding of the sequences was performed independently by two trained analysts to ensure reliability. To assess inter-observer reliability, weighted Cohen's Kappa correlation coefficients were used. The results ranged from 0.78 to 0.84, indicating high agreement (Altman, 1991). The analysed variables included: league (Euroleague and NCAA DI), three-point shot effectiveness (successful and unsuccessful shots), type of offensive execution (transition, second chance from offensive rebound and set plays), time i.e., the timing of the three-point shot within the offensive possession, categorized as beginning (first 6 seconds), middle (7-18 or 7-24 seconds), and end (last 6 seconds) of the possession, player position (guard, forward, and pivot/center), and the half in which the shot was attempted (first and second half).

Analysis

Data processing and statistical analysis were conducted using the SPSS software package version 29. To determine whether differences existed among the examined variables in relation to three-point shot

effectiveness and game outcomes, Crosstabulation Analysis with the Chi-square (χ^2) test was employed, with a significance level set at $p < .05$. Since the χ^2 test measures possible differences between observed and expected values, the Adjusted Standardized Residual was used to identify the specific cell contributions to the independence of variables. Values of the residuals exceeding ± 1.96 ($p = .05$) indicate significant deviations from expected frequencies, pinpointing where significant associations occur within the contingency tables.

RESULTS

Overall, the three-point shooting accuracy reached 36.9% (n = 3249). The Euroleague demonstrated the highest shooting percentage, with 38.4% (n = 1774), while the NCAA Division I recorded a shooting accuracy of 35.1% (n = 1475). To compare the variable league (Euroleague vs. NCAA Division I) in relation to the observed variables, Crosstabulation Analysis with the Chi-square (χ^2) distribution was conducted. Statistically significant differences were identified among the categories of the variable type of offensive execution, $\chi^2(2) = 20.84$, $p < .001$. Fast-break plays and early options accounted for 17.4% of all offensive executions, second-chance opportunities following offensive rebounds accounted for 7.4% and organized offensive sets (set plays) represented 75.3% of all attempts. Specifically, the NCAA Division I demonstrated a higher frequency of transition plays (9.4%) compared to the Euroleague (8%), within the total 17.4% of transition-based attempts. However, this trend did not correspond to shooting efficiency. The shooting percentage in transition was notably lower in NCAA Division I (32.8%) compared to the Euroleague (39%) as presented in Figure 1. Shooting effectiveness in second-chance attempts after offensive rebounds was similar across both leagues (38.3%). However, in set-play situations, Euroleague teams achieved higher shooting accuracy (38.4%) compared to their NCAA counterparts (35.5%).

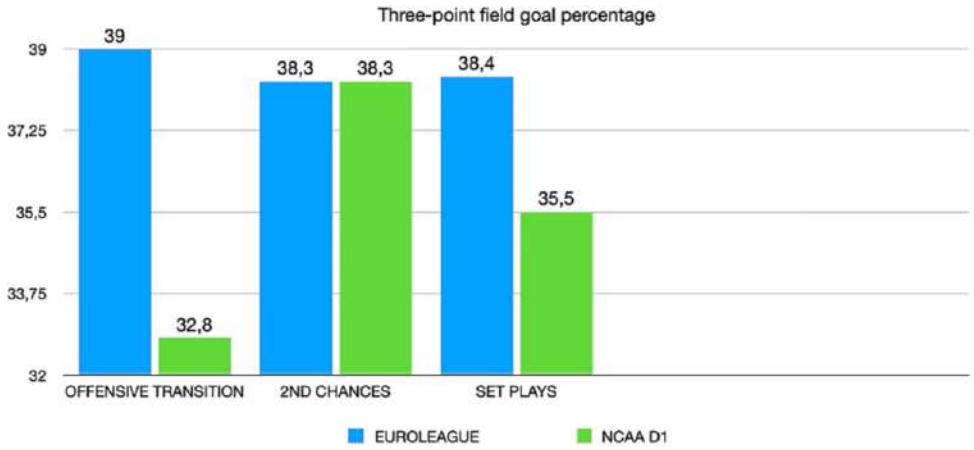

Figure 1. Comparison of three-point shooting percentages between Euroleague and NCAA Division I based on offensive execution type.

Similarly, regarding the timing of the three-point shot within the offensive possession, statistically significant differences were identified ($\chi^2(2) = 206.52$, $p < .001$). Three-point shot attempts were distributed as follows: 13.1% at the beginning of the offense, 61.5% in the middle phase, and 25.5% at the end of the offense.

Notably, in the Euroleague, 19.4% of the shots occurred at the end of the possession compared to only 6.1% in the NCAA, despite both showing lower shooting effectiveness in this phase (33.9% and 32.3%, respectively). Conversely, shot attempts at the beginning of the offense accounted for 6% in the Euroleague

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and 7.1% in the NCAA, with respective shooting percentages of 39.7% and 33.5%. For both leagues, the middle phase of the offensive possession yielded the highest shooting efficiency, with 41.2% for the Euroleague and 36.1% for the NCAA Division I (Figure 2).

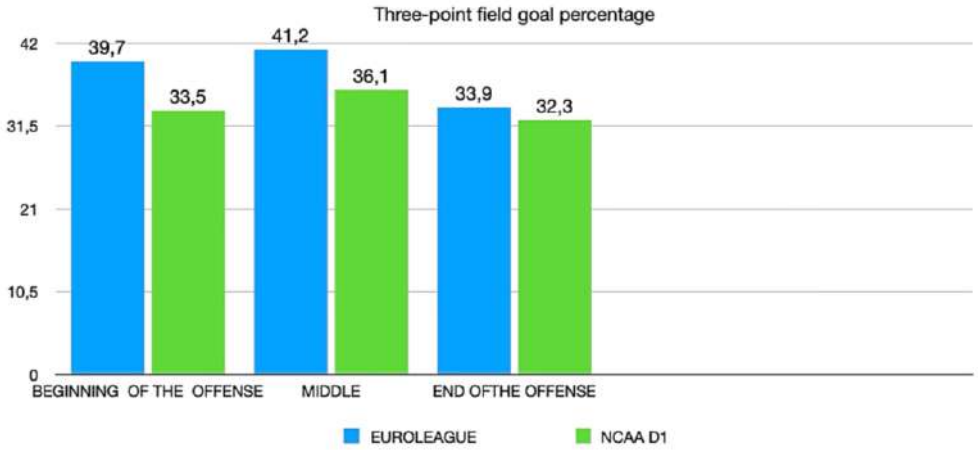

Figure 2. Comparison of three-point shooting effectiveness between Euroleague and NCAA Division I according to shot timing within the offensive possession.

Regarding the categorical variable of player position, statistically significant differences were also found ($\chi^2(2) = 30.79$, $p < .001$). Guards accounted for 59.7% of all three-point shot attempts, with shooting percentages of 38.3% (Euroleague) and 36.4% (NCAA), respectively. Forwards executed 35.8% of the total attempts, while pivots/centers contributed only 4.4% of the shots. In terms of shooting effectiveness, Euroleague forwards recorded the highest percentage with 39.3%, whereas NCAA forwards exhibited the lowest with 33.4% (Figure 3).

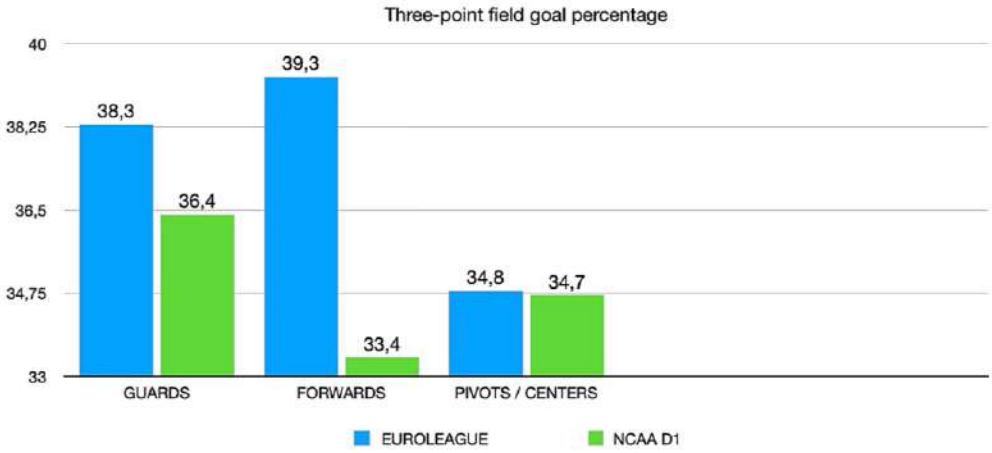

Figure 3. Comparison of three-point shooting effectiveness between Euroleague and NCAA Division I by player position (guard, forward, center).

Concerning the variable game half (first or second half), statistically significant differences were observed ($\chi^2(1) = 5.26$, $p = .032$), as more three-point shot attempts were recorded in both halves of Euroleague games compared to NCAA games.

When examining the relationship between three-point shot effectiveness (successful vs. unsuccessful attempts) and the variable type of offensive execution, no statistically significant differences were found ($\chi^2(2) = 0.636$, $p = .728$), nor were there significant associations with position of the player ($\chi^2(2) = 0.806$, $p = .668$) or game half ($\chi^2(1) = 2.96$, $p = .085$). However, statistically significant differences were observed with respect to the variable timing of the three-point shot within the offense ($\chi^2(2) = 6.34$, $p = .042$), as unsuccessful shot attempts were predominant across all stages of the offensive sequence.

The CHAID analysis (Figure 4) revealed that the championship leagues (Euroleague or NCAA) are significantly differentiated based on the timing of the shot, the player's position, and shot effectiveness. Specifically, timing of the three-point shot within the offense emerged as the most decisive discriminating factor ($p < .001$), showing that three-point attempts executed during the final seconds of the possession were associated with the Euroleague in 76.1% of cases, compared to only 23.9% in NCAA games. This finding suggests a more controlled and patient offensive approach in Euroleague games. In contrast, shots taken during the early or middle phases of the offensive possession were more frequently observed in NCAA games (52.7%) compared to Euroleague games (47.3%), suggesting distinct tempos and shot timing strategies between the two leagues. Furthermore, among shots taken in the early or middle phases, player position also proved to be a significant distinguishing factor ($p < .001$). Guards displayed a relatively balanced distribution between the leagues (Euroleague: 51.7%, NCAA: 48.3%), while forwards and pivots/centers were markedly more involved in NCAA attempts (59.0%) compared to Euroleague (41.0%).

Lastly, within the subset of forwards and pivots/centers, shot effectiveness further differentiated outcomes ($p = .011$). Missed attempts were more frequent in NCAA games (62.0%) compared to Euroleague (38.0%), while successful attempts were more evenly distributed (NCAA: 53.8%, Euroleague: 46.2%).

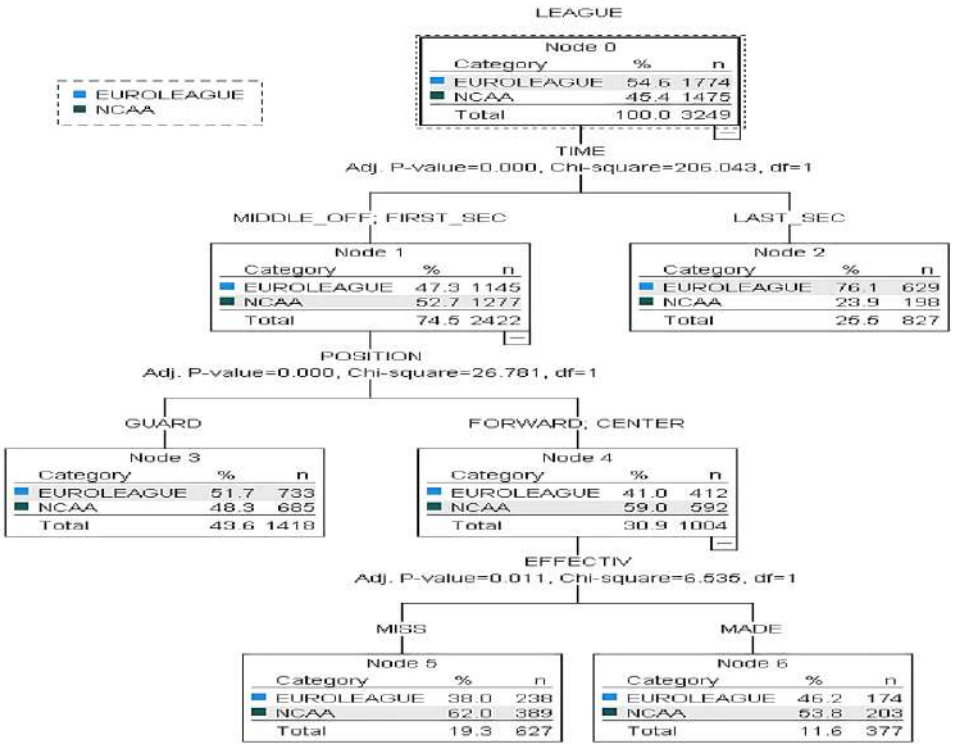

Figure 4. CHAID decision tree analysis identifying key predictors that distinguish between Euroleague and NCAA Division I, with a focus on shot timing, player position, and shooting effectiveness.

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DISCUSSION

The findings of the study demonstrated a distinct divergence between the Euroleague and NCAA Division I regarding tactical approaches and the effectiveness of three-point shooting. These results reflect distinct basketball philosophies across the two competitions-leagues, which appear to influence the frequency, timing, and efficiency of offensive executions.

The timing of the three-point shot within the offense emerged as the most significant differentiating factor, confirming that Euroleague teams tend to attempt more three-point shots at the end of possessions compared to their NCAA counterparts. The higher shooting frequency at the end of possessions (19.4%), combined with a shooting percentage of 33.9%, supports the notion that European teams adopt more structured and patient offensive strategies, a finding also reported by Csataljay et al. (2013). In contrast, NCAA teams are more likely to execute shots during the early or middle phases of possessions, likely due to the up-tempo pace and greater emphasis on the transition game (Oliver, 2004). In other words, Euroleague offenses are marked by greater patience and deliberate shot selection, while NCAA teams show a tendency toward quicker, earlier options.

The results also demonstrated that the player's position influences the type and efficiency of three-point shots. While guards account for the largest share of shot attempts, a finding that coincides with a previous study (Foteinakis & Pavlidou, 2024b), Euroleague forwards exhibited the highest efficiency (39.3%), which may indicate a tactical preference for high-quality, well-selected shooting situations. Conversely, the higher frequency of attempts by forwards and pivots/centers in NCAA games, combined with their lower shooting percentages, may reflect the developmental nature of the collegiate competition (Ibáñez et al., 2018) or emerging trends in the modern game (Oliver, 2004).

Differences related to the variable type of offensive execution indicated that NCAA teams rely more heavily on transition game, characterized by an open, up-tempo pace, compared to Euroleague teams, despite being less effective in converting those opportunities. Nonetheless, both leagues demonstrated a clear predominance of organized offensive structures (set plays), indicating a coaching-driven approach in offensive design.

The CHAID analysis further confirmed the critical importance of shot timing, player position, and shooting effectiveness as key discriminators between leagues. The hierarchical structure of the decision tree revealed that missed three-point attempts by forwards and pivots/centers during early offensive phases were more strongly associated with NCAA play, in contrast to the more targeted and efficient shooting patterns observed in the Euroleague. Guards demonstrated similar performance patterns across both leagues. Overall, the decision tree findings suggest that Euroleague teams are characterized by patience and precision in their offensive possessions, with a tendency to shoot later in the shot clock. In contrast, NCAA teams exhibited higher intensity and up-tempo, with more early shot attempts, especially from taller players, who displayed lower levels of shooting efficiency (Oliver, 2004).

This present study has two main limitations: first, its focus on a single competitive season (2020–21), based on the analysis of 70 games; and second, the coding of selected possessions, although reliable and conducted by two trained researchers, may still involve interpretative discrepancies.

CONCLUSIONS

This study identified significant differences between the Euroleague and NCAA Division I in terms of execution strategies and the effectiveness of three-point shooting. The analyses demonstrated that the timing of the shot, the player's position, and shooting efficiency were key differentiating factors between the two leagues. Specifically, the Euroleague relied heavily on structured offensive schemes, with an increased emphasis on set plays and higher shooting accuracy when the shot was taken at the end of the possession. In contrast, the NCAA was characterized by more immediate offensive execution, with a higher frequency of transition game and lower overall effectiveness in three-point shooting, particularly when shots were taken early in the possession by forwards and pivots/centers.

These findings align with the broader theoretical framework suggesting that European basketball emphasizes tactical discipline and offensive patience, whereas the NCAA tends to adopt a more open and dynamic style of play. From a practical standpoint, the results can serve as valuable insights for coaches, performance analysts, and sports scientists in optimizing offensive strategies and guiding player development based on the distinct profiles and demands of each competition - league.

In summary, further investigation of the differences between the Euroleague and NCAA Division I may enhance knowledge exchange between the two leagues and consequently contribute to the overall development of the sport at a global level.

AUTHOR CONTRIBUTIONS

G. Karamousalidis design of the study, data analysis and writing the manuscript. A. Kourtis-Doulkeridis & G. Konstantinidis data collection and review. P. Foteinakis & D. Kifonidis review and manuscript preparation. S. Symeonidou & P. Foteinakis statistical analysis. All authors have approved the final version of the manuscript.

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No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Score analysis of ankle joint laxity and the incidence of ankle injury in professional female athletes: A retrospective study

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ABSTRACT

Ankle injury occurs in 45% of sports injuries, and as many as 14% of them is severe injuries. This condition is quite common in athletes such as athletics. The current solution for athletes with joint instability is to take preventive measures to minimize the possibility of injury. This study aims to analyse the instability score on the incidence of ankle injuries in female professional athletes. This retrospective study analysed data from professional female athletes to assess the incidence of ankle injuries in relation to their history of ankle instability. The study involved evaluating ankle instability using the Beighton score, the AOFAS score, and a detailed history of prior ankle injuries. Out of the total sample, 168 female athletes were identified, with 141 (80%) reporting a history of ankle injuries. The most frequent injury was ankle-related, occurring in 28% of the sample. Among those with prior ankle injuries, 83% (30 out of 36) showed a positive result on the Beighton score. The AOFAS evaluation revealed that 25% (12 athletes) had excellent ankle function, while 75% (36 athletes) demonstrated superb function. The use of the Beighton score and AOFAS score for evaluating professional female athletes with a history of ankle injuries proves to be effective in identifying those at higher risk for future injuries, thereby aiding in prevention strategies.

Keywords: Sport medicine, Ankle injury, Female athlete, Beighton score, Joint laxity.

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INTRODUCTION

Incidence of ankle injury is one of the most common athletic injuries. This injury occurs in 45% of sports injuries, and as many as 14% of them can be considered severe injuries (Park et al. 2016; Yeo et al. 2017). This condition is quite common in athletes such as athletics. Many individuals with joint instability participate in athletic activity programs (Bullock et al. 2020; Halabchi and Hassabi 2020; Liaghat et al. 2021; Prieto-González et al. 2021). The impact that occurs if joint instability is not appropriately handled, from prevention to definitive therapy, will cause early osteoarthritis (OA). The incidence of early osteoarthritis in athletes can cause a decrease in performance. The most fatal can cause early retirement in athletes at an age due to joint instability that repeatedly occurs (Saccomanno et al. 2013; Sacks et al. 2019).

The current solution for athletes with joint instability is to take preventive measures to minimize the possibility of injury. Preventive measures other than stretching can also include screening in the form of a physical examination of the joints and a training program that is by the portion and needs of the athlete to prevent more severe injuries (Kemler, Valkenberg, and Gouttebarge 2019; Saccomanno et al. 2013; Talpey and Siesmaa 2017).

This study aims to analyse the instability score on the incidence of ankle injuries in female professional athletes. The results of the score analysis is expected to provide benefits in the form of a description of the injury to professional female athletes with a particular score so that it can be used to prevent more severe injuries.

METHOD

Participants

The sample population in this study were female professional athletes with inclusion criteria as follows: Female Professional Athlete with a history of injury to the joints has a history of a previous ankle injury, is cooperative, can communicate, and can answer questions asked and is willing to be examined. Samples with a history of ankle surgery were excluded from the study criteria. The sample was then identified according to the inclusion criteria. Data was collected through an ankle instability examination based on the Beighton score criteria and a history of previous ankle injuries. Then, we analysed the scores on ankle instability and the incidence of injury in female professional athletes using the AOFAS. The data is presented in descriptive form.

Procedures

This study uses a descriptive observational design with retrospective data collection to determine the incidence of ankle injuries in professional female athletes adjusted for the results of an ankle instability examination (based on the Beighton score). The American Orthopedic Foot and Ankle Association (AOFAS) score determines the history of injury, examination injury screening, and the functional performance of female professional athletes. Letter of Exemption with Referral number 0819/LOE/301.4.2/II/2022 obtained on March 12th 2022**.**

Data analysis

The collected data was analysed using Statistical Package for the Social Sciences v.26 (SPSS; IBM, SPSS Inc., USA). The data was analysed in univariate and multivariate using chi-square and Mann Whitney. Statistical result $p < .05$ was determined as statistically significant.

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RESULTS

In this study, from the distribution of samples by gender, the number of female athletes was 168 (51%), and male athletes were 159 (49%). Of those 168 female athletes, there were 141 who suffered injuries (80%) (Table 1).

Table 1. Patient demographic data.

Demographic	N (%)
Sex	
Male	159 (49)
Female	168 (51)
Inguring	
Suffered injuries	141 (48)
No injuries	27 (16)
Injuries location	
Ankle	48 (28)
Knee	45 (26)
Shoulder	21 (12.5)
Wrist	6 (3)
Hip	3 (1)
Others	18 (12.8)
Positive beighton score	
History of ankle injury	30 (62.5)
Without history of ankle injury	6 (12.5)
AOFAS	
Excellent	12 (25)
Good	36 (75)

From the results of the sample distribution of the types of joint injuries that often occur in female athletes, there were 48 (28%) cases of ankle joint injuries, followed by the second most frequent knee injuries (26%), then 21 cases of shoulder joint injuries. (12.5%), wrist joint injury in 6 cases (3%), hip joint injury in 3 cases (1%), and there are other types of injuries such as hamstring muscle injury and plantar fasciitis. The results were obtained from 48 athletes who had ankle injuries, 36 athletes who had a history of previous ankle injuries (75%), and 10 athletes who had positive Beighton scores from 36 athletes (83%). The highest number of ankle injuries is lateral ankle injury found in 43% of female athletes (21 athletes), followed by Chronic Ankle Injury (CAI) and medial ankle injury in 8 athletes (16%), and also talofibular syndesmosis tear and osteochondritis dissecans of the talus found in 8% and 2% of the athletes (4 and 1 athlete), respectively. From the data obtained, as many as 12 athletes who do not have a history of an ankle injury from 48 athletes (25%) received as many as 6 athletes who have a positive Beighton score out of 12 athletes (50%).

An evaluation was obtained with AOFAS scores on 48 athletes with ankle injuries, 12 athletes out of 48 athletes (25%) with ankle injuries in the excellent category. A total of 36 athletes out of 48 athletes (75%) who experienced ankle injuries were in a suitable class. In the evaluation with the AOFAS score, 75% of athletes have a reasonable interpretation.

DISCUSSIONS

From the overall sample, 168 (51%) female athletes were found, of which 141 (80%) had previous injuries. These data are in line with prior studies which stated that joint hypermobility, defined as the presence of an

excess range of motion (ROM) when associated with age, gender, and ethnic group, was more common in women than men (Francia et al. 2021; Gianakos et al. 2022). Women also have a higher chance of experiencing generalized joint laxity (GJL) and GJL. A positive Beighton score will tend to be more prone to ligament injuries and potentially have repeated injuries. Ankle injuries are the highest incidence in several sports in potential and professional athletes, and laxity has a high risk of ankle injuries and injuries to other appropriate joints for the sport.

Injuries most often occur in the ankle (28%) and knee (25%), several factors that can cause the ankle joint to be the most common joint injury experienced by professional female athletes are the type of movement in a sport that is dominated by running, jumping, and sudden changes in motion or while running suddenly are the highest contributing factors for ankle injuries (Arabnejad, Pourranjbar, and Yousefizarandi 2023; Hietamo et al. 2023).

The Beighton score is a measurement tool that is widely used to measure generalized joint laxity. These measurements are easy to perform and can provide reliable interobserver and interobserver results. In this study, after evaluating female professional athletes who had a positive Beighton score, then evaluating female professional athletes with positive Beighton scores who had a history of an ankle injury and no history of an ankle injury (Ganu and Tadge 2021; Malek, Reinhold, and Pearce 2021; Nathan, Davies, and Swaine 2018; Rejeb et al. 2019).

In this study, it was found that there was an increased risk of recurrent ankle injury in female professional athletes who had a previous history of ankle injury with a percentage of 74% based on the Beighton score. In addition, the Beighton Score was positive in 30 of 36 people (83%) who had a previous ankle injury and 6 of 12 people (50%) who did not have a prior ankle injury. From these results, female athletes with a history of an earlier ankle injury and a positive Beighton score were more at risk for recurrent ankle injuries. This may be due to several factors, but a Beighton score indicates a possible correlation between laxity represented by a positive Beighton score for ankle injuries, especially in athletes who have a history of previous ankle injuries.

The AOFAS score is the most widely used clinical scoring system to measure management outcomes in patients with ankle or back foot injuries, with 9 rating scales divided into 3 sub-scales of assessment pain, function, and alignment (Hijji et al. 2020; Paget et al. 2023). From the evaluation results with AOFAS scores on 48 athletes with ankle injuries, it was found that 12 athletes out of 48 athletes (25%) had ankle injuries in the excellent category and 36 athletes out of 48 athletes (75%) had ankle injuries in the excellent category. This is probably because some female professional athletes who have a history of ankle injuries complain of pain that only arises when doing specific movements during sports. The pain only appears when doing precise movements during sports but does not interfere functionally when used in daily activities. The professional athlete also did not find any anatomical misalignment in the ankle and back of the foot.

CONCLUSIONS

Evaluation of professional female athletes who have a history of ankle injury using the Beighton score and the AOFAS score is quite effective in assessing the risk of recurrent ankle injuries and a history of previous ankle injuries that affect the functional ability of the ankle.

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AUTHOR CONTRIBUTIONS

ATD and RPP, both authors make the same contribution to data collection. RPP contributes more to manuscript preparation, writing, and data analysis. ATD contributes more to editing the manuscript and ethical clearance.

SUPPORTING AGENCIES

No funding agencies were reported by the authors.

DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL APPROVAL

Letter of Exemption with Referral number 0819/LOE/301.4.2/II/2022 obtained from Dr. Soetomo General Hospital, Surabaya, Indonesia on March 12th 2022

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ORIGINAL ARTICLE

Muscular strength measurements through hand-held and anchored dynamometry: A study of test-retest and interrater reliability

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ABSTRACT

Background: Hand-held dynamometry (HHD) offers a cost-effective and accessible method for measuring maximal voluntary contraction (MVC) compared to larger fixed dynamometers. This study aimed to determine if fixing the portable HHD device to a support anchor could improve intra- and inter-rater reliability across different muscle groups. Methods: Twelve healthy adults (ages 18–34) participated in two sessions of isometric MVC testing for ten muscle actions, conducted by two raters under both hand-held and anchored conditions. Interrater and intra-rater reliability were evaluated using intraclass correlation coefficients (ICC). Results: The anchored system demonstrated overall excellent interrater reliability (ICC = 0.935), while the hand-held condition yielded good reliability (ICC = 0.895), falling just below the threshold for excellent. Both methods showed overall excellent intra-rater reliability (HHD ICC = 0.933; Anchor ICC = 0.953). The anchored system yielded excellent reliability for elbow extension & flexion, internal & external rotation of the shoulder, plantarflexion, and neck extension, while moderate reliability was observed for knee assessments. Conclusions: Results support the use of anchoring systems to enhance measurement consistency, especially when using multiple raters. Anchored HHD systems may offer a more stable, repeatable method for muscle strength evaluation, benefiting both muscle strength and muscle injury assessments and research protocols.
Keywords: Sport medicine, Muscle strength assessment, Hand-held dynamometry, Interrater reliability, Anchored dynamometer, Maximal voluntary contraction, Isometric force.

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INTRODUCTION

Muscle strength serves as a key indicator of injury recovery progress, overall muscular function, and general health status (Eriksrud & Bohannon, 2003; Byram et al., 2010; Hams et al., 2019; Bohannon, 2021). Muscular strength testing can inform sports and rehabilitation professionals about a patient's injury status and their potential independence outside of the clinical space (Eriksrud & Bohannon, 2003; Byram et al., 2010; Hams et al., 2019; Bohannon, 2021). Moreover, recent research has highlighted muscle strength as a potential biomarker for all-cause mortality and cardiovascular disease, even when adjusting for potential confounds (García-Hermoso et al., 2018; Yusuf et al., 2020). This emphasizes the need of accurately assessing muscle strength for athletes. These measures are typically obtained via maximal volitional contractions (MVC) which assesses a muscle or muscle group's maximal voluntary force generation capacity. Although many methods exist for measuring an MVC, such as an isokinetic device or manual muscle testing, hand-held dynamometry (HHD) provides an inexpensive and more accessible (Dollings et al., 2012) alternative for MVC measurements due to its minimal setup, space requirements, and cost.

Previous research underscores the reliability of HHD as an effective tool for obtaining objective measurements of muscular strength across various muscle groups (Johansson & Adolfsson, 2005; Whiteley et al., 2012; Alnahdi et al., 2014; Fieseler et al., 2015; Holt et al., 2016; Conceição et al., 2018; Croteau et al., 2021). However, HHD presents significant challenges that must be addressed to ensure more accurate measurements, such as strength disparities between the rater and the subject and inconsistent placement of the dynamometer (Wikholm & Bohannon, 1991; Bohannon et al., 2012; Thorborg et al., 2013). These factors seem most prevalent and commonly reported when assessing muscles in the lower extremities. Early research by Wikholm and Bohannon (1991) found that muscle groups producing greater isometric force (i.e., knee extensors) had greater variation in measurement compared to weaker muscle groups (i.e., shoulder external rotators). The authors also reported that the magnitude of force measurements varied depending on the strength of the rater or examiner.[15] Thorborg and coworkers (2013) also found a significant between-tester bias in measuring hip strength with HHD suggesting the stronger the subject, the larger the bias. Grootswagers et al. (2022) found that HHD systematically overestimated leg extension and flexion force in older adults compared to torque values obtained by an isokinetic device. Considering these confounds, improving the reliability of HHD is a pressing need for all health professionals as it will increase their confidence in the measures and improve their ability to assess musculoskeletal function and health.

Prior research has also examined externally supported dynamometers as a means to significantly enhance HHD's reliability (Byrne et al., 2020). Recently, Lafayette Instruments has developed a Hand-Held Dynamometer support stand (Model 1066), which anchors the Dynamometer (Model 01165), one of the most widely used HHDs in skeletal muscle research. The anchor is structured so that the HHD is fixated to a metal arm extending from the vertical base that is attached to a platform the tester can stand on. Two handles extend from either side of the base, providing extra leverage for the tester during MVCs which decreases strength bias between the tester and subject. The present research aims to observe the effects of utilizing the support stand anchor on interrater and intra-rater reliability across multiple joints and muscle groups in two separate sessions. The present study design incorporates test-retest assessments of ten distinct isometric muscle actions: knee extension, knee flexion, elbow extension, elbow flexion, internal rotation of the shoulder, external rotation of the shoulder, dorsiflexion, plantarflexion, neck extension, and neck flexion. It was hypothesized that the use of the Model 01166 support stand would improve interrater and intra-rater reliability across the ten muscle actions.

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METHODS

Subjects

The subject population for the present study was twelve adults (n = 12), ages 18-34. Subject characteristics by sex are reported in Table 1. All participants within the study needed to satisfy the exclusion criteria: i) individuals less than 18 or older than 34 years old, ii) history of significant body injury (e.g., ligament tears, complete bone fracture, Grade III musculotendon tears), iii) history of medical neurological, or musculoskeletal impairments that could affect force measurements. Any potential subject who listed exclusionary criteria was dismissed from participating in the study. Due to unforeseen scheduling issues, Rater 2 did not collect Day 2 measurements for Subject 1; therefore, this timepoint was omitted from intra- and inter-session analyses.

Table 1. Subject characteristics.

	Males (n = 7)	**Females (n = 5)**
Age (y)	21.4 ± 4.0	19.4 ± 1.3
Height (cm)	180.0 ± 5.8	169.9 ± 7.6
Mass (kg)	94.1 ± 25.0	79.4 ± 7.7
BMI (kg/ m^2)	28.9 ± 7.0	27.5 ± 1.3

Note. Values are means ± SD. y, years. cm, centimeters. kg, Kilograms. m^2, meters-squared.

Experimental design

Subjects reported to the testing area for the first session, during which they received an introduction and a thorough explanation of the study. The current study was approved by the Institutional Review Board and informed consent was obtained during this time. Additionally, a health history questionnaire was administered to assess the eligibility of the participants for the study. Individuals were excluded if they were under 18 or over 34 years of age, or had a history of significant injury (e.g., ligament tears, fractures, Grade III musculotendinous tears) or medical, neurological, or musculoskeletal conditions affecting torque production.

Following introductory procedures, subjects warmed up for 5 minutes on an elliptical before beginning strength assessments. After warming up, the participants prepared for the strength assessments scheduled for that day. The subjects performed MVCs for each muscle action on a hand-held Dynamometer (Hand-held Dynamometer Model 01165A; Lafayette Instruments, Lafayette, IN, USA) on two separate days within a maximum of seven days (i.e., one week) in-between sessions. There was an average of 3.3 days in-between sessions. Two raters recorded strength measurements under two conditions: one while holding the dynamometer and the other while collecting measurements with the device fixated to the anchor (Model 01166; Lafayette Instruments, Lafayette, IN, USA). Rater 1 is male, and Rater 2 is female. Peak handgrip force for each rater was taken in a series of three attempts with their dominant hand prior to the first subject's data collection with a handgrip dynamometer (Smedley Digital Hand Dynamometer Model 12-0286; Baseline, Fabrication Enterprises Inc, White Plains, NY, USA). Rater 1 had a peak handgrip strength of 58.4 kg and Rater 2 had a peak handgrip strength of 36.6 kg. The raters were trained in hand-held strength testing assessment for approximately 5-6 hours in total over the course of five sessions before data collection began. During hand-held trials, raters were allowed to record the measurements however they were most comfortable, helping minimize error, including using a chair or wall for support. The testing order was a controlled variable and was performed in the order presented below. All assessments were completed on the subject's dominant leg and arm while sitting or lying on an athletic training or treatment table. Once all MVCs for a muscle group and corresponding range of motion were complete on the first condition (i.e., Hand-held vs. Anchored), the subject repeated the assessment under the second condition with the same rater before

proceeding to the next muscle group. Once all measurements for all assessments were complete with the first rater, the procedures were repeated with the second rater.

Maximal voluntary contraction strength assessments

The strength of ten different muscle actions was assessed on both testing days. The order of the strength assessments was constant throughout each session and between each subject. During initial intake, subjects provided their upper and lower body dominance (i.e., left-handed and right-footed or right-handed and right-footed). Each strength assessment was performed on the subject's dominant side for the upper and lower extremities. The order of the two conditions (HHD and Anchor) was randomized for each subject; for example, subject one could have performed anchored first, while subject two performed hand-held dynamometry first. Before each MVC trial on both days, subjects completed a practice repetition to introduce the movement. Subjects then performed two recorded MVCs for each condition (Hand-held and Anchored). The dynamometer was tared before each attempt. Each MVC lasted four seconds. Subjects were instructed and vocally encouraged to exert maximum force until told to stop at the end of the four seconds. There was a 90-second rest period between each repetition. A digital clock would countdown periods of rest and effort for the subject. If a mistrial occurred due to errors (i.e., movement of the base or rater during testing; deviation of joint angle during test; force reading inconsistency; subject pain) the trial was redone after the subject rested to ensure accurate measurement. Data from mistrials were excluded from analysis to maintain consistency and reliability.

Knee extension

Subjects sat upright on the edge of the testing table with both hands resting on their thighs or the side of the table, ensuring consistency in hand placement throughout the assessment. Using a hand-held goniometer (EZ Read Jamar Goniometer, Sammons Preston), the rater positioned their dominant leg in 90° knee flexion with both their hip and ankle joints at 90°. For both conditions, the rater positioned the dynamometer ~ 2 cm above the talus bone on the anterior side of the dominant leg. During HHD attempts, the rater was positioned in a chair against the wall, directly in front of the subject on the table. During anchored trials, the dynamometer was attached to the arm of the anchor, placed adjacent to the dominant leg, and adjusted in height to account for individual differences in anthropometrics. The rater supported the anchor by standing in a split stance and braced to resist each contraction.

Knee flexion

Subjects sat upright on the edge of the testing table with their hands resting either on their thighs or the sides of the table, ensuring consistency in hand placement throughout the assessment. The rater positioned the dynamometer ~ 2 cm above the talus bone on the posterior side of the dominant leg. For HHD trials, the rater sat in front of the subject, resisting the subject pulling their leg. During anchored trials, the dynamometer was attached to the arm of the anchor and placed behind the dominant leg. The rater supported the anchor in a split stance and braced to resist each contraction.

Elbow flexion

Subjects sat upright on the edge of the testing table with their non-dominant hand resting on their thigh while their dominant arm rested in 90° elbow flexion with the forearm in supination. The subject was instructed to pin a hand towel against their ribcage on their dominant side using their upper arm to ensure that it stayed fixated at their side during the assessment. The rater stood adjacent to the subject and rested the dynamometer proximal to the radial styloid process on the subject's radial surface of their forearm. For the HHD condition, the rater resisted the movement downward. During the anchor condition, the rater stood on top of the anchor platform to prevent it from sliding or tipping over.

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Elbow extension
Subjects lay supine with their head near the end of the testing table. Their non-dominant hand rested at their side, while the dominant arm was positioned in 90° shoulder flexion and 90° elbow flexion, with the forearm in neutral supination. The rater stood adjacent to the subject and positioned the dynamometer proximally to the ulnar styloid process on the ulnar surface of the forearm. For the HHD condition, the rater resisted the movement downward. During the anchor condition, the rater stood on top of the anchor platform to prevent it from sliding or tipping over.

Internal rotation of the shoulder
Subjects lay supine with their head near the end of the testing table. Their non-dominant hand gripped the side of the table to prevent sliding, while the dominant arm was positioned at 45° of shoulder abduction and 90° of elbow flexion. The dynamometer was placed on the anterior forearm proximal to the ulnar styloid, with the forearm in neutral supination. For the HHD condition, the rater resisted the movement by pulling against the arm of the subject. During the anchor condition, the anchor was positioned adjacent to the dominant side, and the rater stood on top of the anchor platform to prevent it from sliding or tipping over.

External rotation of the shoulder
Subjects lay supine with their head near the end of the testing table. Their non-dominant hand gripped the side of the table to prevent sliding, while the dominant arm was positioned at 45° of shoulder abduction and 90° of elbow flexion. The dynamometer was placed on the posterior forearm proximal to the ulnar styloid, with the forearm in neutral supination. For the HHD condition, the rater resisted the movement by pulling against the arm of the subject. During the anchor condition, the anchor was positioned adjacent to the dominant side, and the rater stood on top of the anchor platform to prevent it from sliding or tipping over.

Dorsiflexion
Subjects lay supine with their hips and knees extended and their ankle joint positioned at 90°. The dynamometer was placed over the metatarsal heads on the dorsum of the dominant foot. In the HHD condition, the rater was seated at the end of the testing table in a chair against the wall, with arms fully extended to resist movement during measurements. During the anchor condition, the raters supported the anchor in a split stance and braced to resist each contraction.

Plantarflexion
Subjects lay supine with their hips and knees extended and their ankle joint positioned at 90°. The dynamometer was placed over the metatarsal heads on the plantar surface of the dominant foot. In the HHD condition, the rater was seated at the end of the testing table in a chair against the wall, with arms fully extended to resist movement during measurements. During the anchor condition, the raters supported the anchor in a split stance and braced to resist each contraction.

Neck extension
Subjects lay prone on the testing table, with arms in a comfortable position by their sides and the head hanging off the front edge of the table. The neck rested in a neutral hang position while the dynamometer was placed on the back of the subject's head (crown). For the HHD condition, the rater resisted the movement downward. During the anchor condition, the rater stood on top of the anchor platform, which was positioned in the same manner as the rater in the HHD condition, to prevent it from sliding or tipping over.

Neck flexion
Subjects lay supine on the testing table, with arms in a comfortable position by their sides and the head resting near the edge of the table. For comfort, a bolster was placed under the posterior side of each subject's

neck. The dynamometer was placed on the subject's forehead. For the HHD condition, the rater resisted the movement downward. During the anchor condition, the rater stood on top of the anchor platform, which was positioned in the same manner as the rater in the HHD condition, to prevent it from sliding or tipping over.

Data analysis and statistics

Test-retest data was analysed using the intraclass correlation coefficient (ICC) analysis. ICC serves as a measure of repeatability that evaluates both the degree of correlation and agreement between measurements (Koo & Li, 2016). ICC values below 0.5 are considered to have poor reliability, between 0.5 and 0.75 are considered moderate reliability, 0.75 and 0.9 are considered good reliability, and greater than 0.90 is considered excellent reliability based on a 95% confidence interval (Koo & Li, 2016). A Two-way mixed model with absolute agreement was used to calculated interrater and intra-rater ICCs. Statistical analysis was conducted using SPSS (IBM) Version 29 and Excel (Microsoft Office 2021).

RESULTS

Table 2. Mean isometric MVC force.

Muscle action	Rater	HHD day 1	HHD day 2	Anchor day 1	Anchor day 2
KE	1	415.8 ± 103.4	404.3 ± 104.6	313.9 ± 68.4	309.1 ± 58.7
	2	360.2 ± 93.5	318.9 ± 87.2	322.2 ± 69.2	296.3 ± 66.1
	Total	388.0 ± 100.5	363.5 ± 104.1	318.0 ± 67.4	303.0 ± 61.2
KF	1	179.63 ± 73.2	208.8 ± 57.8	109.6 ± 34.8	128.2 ± 31.3
	2	211.0 ± 75.3	226.8 ± 78.5	139.8 ± 37.2	152.5 ± 46.1
	Total	195.3 ± 74.4	217.4 ± 67.5	124.7 ± 38.5	139.8 ± 40.1
EF	1	225.3 ± 77.1	215.2 ± 77.3	236.6 ± 82.6	214.8 ± 75.0
	2	244.3 ± 89.1	249.8 ± 101.1	209.4 ± 65.3	228.4 ± 86.2
	Total	234.8 ± 82.1	231.7 ± 89.1	223.0 ± 74.1	221.3 ± 79.0
EE	1	167.3 ± 79.5	171.7 ± 85.1	171.9 ± 76.4	166.1 ± 77.4
	2	182.3 ± 86.9	190.6 ± 92.7	164.0 ± 54.4	170.5 ± 74.0
	Total	174.8 ± 81.8	180.7 ± 87.3	168.0 ± 65.0	168.2 ± 74.1
IR	1	168.5 ± 70.2	163.8 ± 59.5	165.4 ± 64.39	147.7 ± 53.4
	2	180.0 ± 54.7	178.0 ± 70.5	151.5 ± 44.5	148.5 ± 58.1
	Total	174.3 ± 61.9	170.6 ± 63.9	158.5 ± 54.9	148.0 ± 54.4
ER	1	143.8 ± 57.0	141.9 ± 45.8	131.7 ± 53.7	129.1 ± 40.5
	2	144.4 ± 54.8	151.0 ± 51.5	136 ± 51.9	134.2 ± 52.5
	Total	144.1 ± 54.7	146.3 ± 47.7	133.8 ± 51.7	131.5 ± 45.6
DF	1	195.6 ± 63.8	197.7 ± 48.0	164.8 ± 30.6	161.8 ± 30.6
	2	214.9 ± 83.8	204.4 ± 68.7	171.5 ± 40.6	165.0 ± 27.8
	Total	205.3 ± 73.5	200.9 ± 57.5	168.2 ± 35.4	163.3 ± 28.7
PF	1	347.3 ± 68.4	347.8 ± 82.8	336.8 ± 83.3	334.0 ± 73.2
	2	313.3 ± 97.5	302.4 ± 102.9	315.8 ± 62.3	327.1 ± 61.6
	Total	330.3 ± 84.2	326.0 ± 93.7	326.3 ± 72.8	330.7 ± 66.4
NE	1	183.2 ± 88.9	170.8 ± 51.7	196.8 ± 89.6	188.8 ± 67.9
	2	206.6 ± 74.3	199.6 ± 85.8	200.1 ± 71.4	188.8 ± 77.2
	Total	194.9 ± 80.8	184.5 ± 69.8	198.5 ± 79.1	188.8 ± 70.6
NF	1	112.7 ± 45.5	111.1 ± 36.9	134.3 ± 53.2	135.0 ± 55.1
	2	145.1 ± 59.5	152.9 ± 64.7	124.3 ± 37.1	142.6 ± 52.7
	Total	128.9 ± 54.4	131.1 ± 55.1	129.3 ± 45.2	138.7 ± 52.9

Note. Mean force values (±SD) in Newtons for each muscle action measured by both raters across two testing days using hand-held dynamometry (HHD) and anchored methods. KE = Knee Extension, KF = Knee Flexion, EF = Elbow Flexion, EE = Elbow Extension, IR = Internal Rotation, ER = External Rotation, DF = Dorsiflexion, PF = Plantarflexion, NE = Neck Extension, NF = Neck Flexion.

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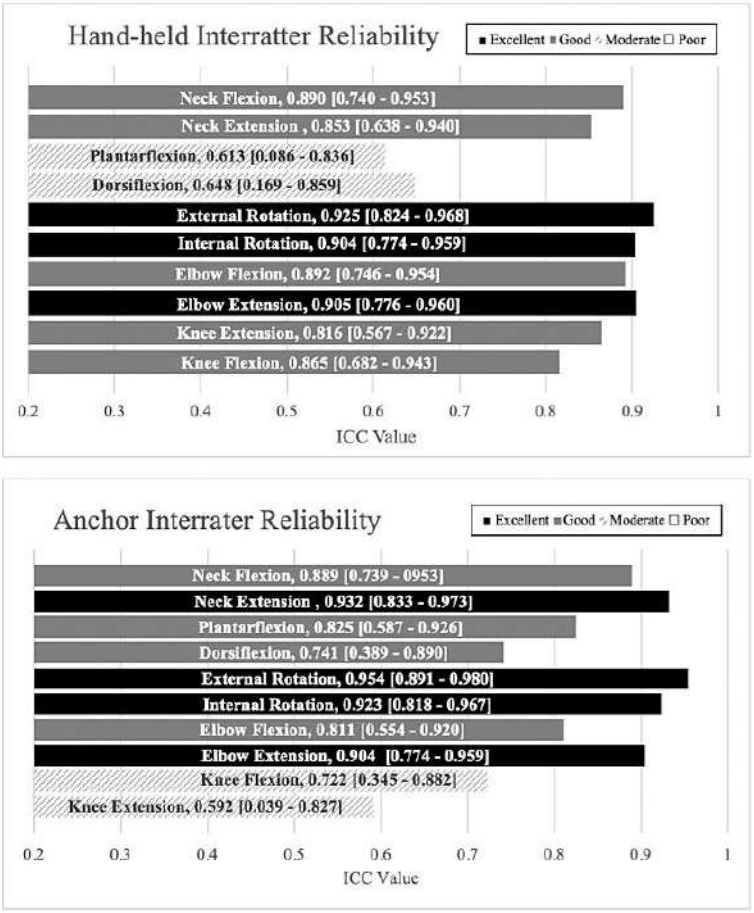
Reliability analysis

Force values for each muscle group, measured by both raters across both days using HHD and anchored methods, are reported in Table 2.

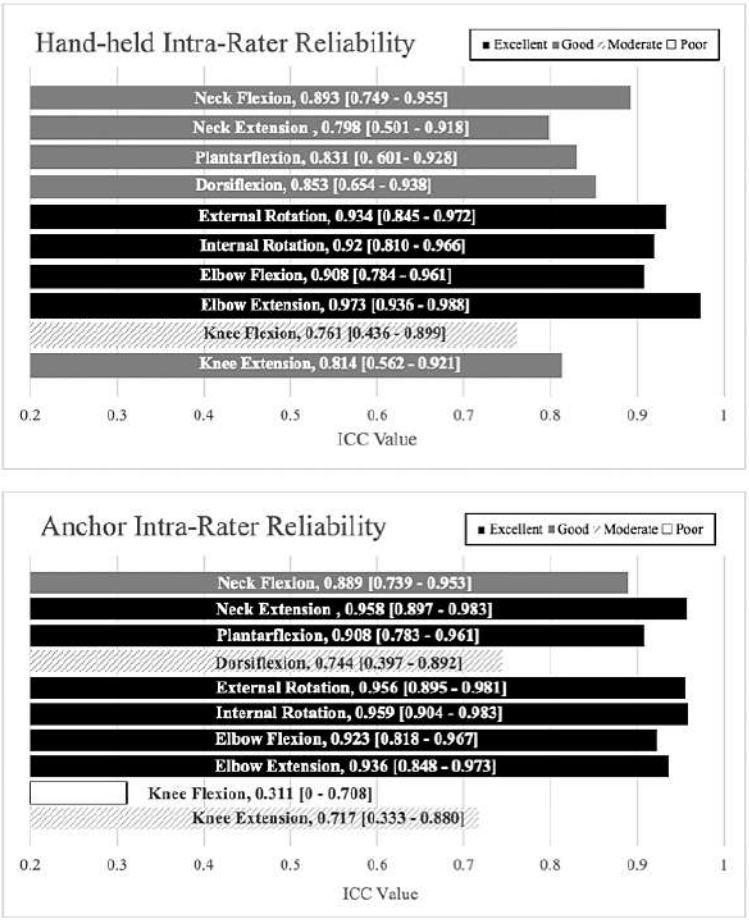
The total interrater reliability for hand-held dynamometry (HHD) was good (ICC = 0.895, 95% CI = 0.864 – 0.919), while the anchored method showed excellent reliability (ICC = 0.935, 95% CI = 0.915 – 0.950). Total intra-rater reliability was excellent for HHD (ICC = 0.933, 95% CI = 0.913 – 0.949) and anchored (ICC = 0.953, 95% CI = 0.940 – 0.964). Interrater and intra-rater reliability, as measured by Intraclass Correlation Coefficients (ICCs), are presented visually in Figures 1 and 2, respectively, for both HHD and anchored conditions across all muscle actions tested. Interrater reliability with HHD ranged from moderate to excellent (ICC = 0.613 to 0.925). Excellent reliability was observed for internal & external rotation of the shoulder as well as elbow extension. Good reliability was observed for knee flexion, knee extension, elbow flexion, neck extension, and neck flexion. Moderate reliability was observed for plantarflexion and dorsiflexion. With the anchored method, interrater reliability ranged from moderate to excellent (ICC = 0.592 to 0.931). Excellent reliability was observed for elbow extension, internal & external rotation of the shoulder, and neck extension. Good reliability was observed for elbow flexion, plantar flexion, and neck flexion. Moderate reliability was observed for knee extension, knee flexion, and dorsiflexion.



Note. Intraclass Correlation Coefficients (ICCs) are shown for each muscle action test. The dashed lines represent thresholds for poor (<0.5), moderate (0.5-0.75), good (0.75-0.9), and excellent (>0.9) reliability.

Figure 1. Interrater reliability of muscle strength measurements using (A) hand-held dynamometry (HHD) and (B) anchored methods.

Intra-rater ICCs ranged from moderate to excellent (0.761 to 0.973) for day-to-day reliability with HHD. Excellent reliability was observed for elbow extension, elbow flexion, internal rotation of the shoulder, and external rotation of the shoulder. Good reliability was observed for knee extension, dorsiflexion, plantar flexion, neck extension, and neck flexion. Moderate reliability was observed for knee flexion. Intra-rater ICCs ranged from poor to excellent (0.311 to 0.959) with the anchored method. Excellent reliability was observed for elbow extension, elbow flexion, internal rotation of the shoulder, external rotation of the shoulder, plantar flexion, and neck extension. Good reliability was observed for neck flexion. Moderate reliability was observed for knee extension and dorsiflexion. Poor reliability was observed for knee flexion.



Note. Infraclass Correlation Coefficients (ICCs) are shown for each muscle action tested. The dashed lines represent thresholds for poor (<0.5), moderate (0.5-0.75), good (0.75-0.9), and excellent (>0.9) reliability.

Figure 2. Intra-rater reliability of muscle strength measurements using (A) hand-held dynamometry (HHD) and (B) anchored methods.

DISCUSSION

Both methods exhibited excellent intra-rater reliability (ICC > 0.9) across all muscle actions, supporting previous findings that individual testers can obtain consistent results under controlled conditions (Whiteley et al., 2012; Byrne et al., 2020). However, the anchored method demonstrated superior interrater reliability (ICC = 0.935) than the hand-held dynamometer (HHD) method (ICC = 0.895). This finding coincides with prior studies highlighting the importance of external fixation for consistent measurements (Aerts et al., 2025;

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Beshay et al., 2011). It is worth noting that the hand-held approach also performed well, nearing the threshold for excellent reliability (ICC > 0.9). For coaches, trainers, researchers, and clinicians, using an anchored system could enhance confidence in muscle strength assessments, particularly in cases where multiple testers are involved or when working with individuals capable of producing high force compared to the tester (Wikholm & Bohannon, 1991; Bohannon et al., 2012; Thorborg et al., 2013).

Notably, elbow extension, internal rotation, and external rotation exhibited excellent interrater reliability (ICCs > 0.9) with the anchored system, paralleling findings from Beshay and coauthors in 2011, which also saw improvements in shoulder strength measurements with external fixation of a dynamometer. Using a stable anchor minimized variability stemming from tester strength and positioning, a recurring limitation of HHD in previous studies (Wikholm & Bohannon, 1991; Bohannon et al., 2012; Thorborg et al., 2013; Grootswagers et al., 2022). Plantarflexion yielded moderate interrater reliability when using HHD (ICC = 0.613). Previous research has shown a wide range of reliability across populations when assessing plantarflexion with rankings from poor (Katoh & Yamasaki, 2009; Marmon et al., 2013) to moderate (Mentiplay et al., 2015) to good (Mentiplay et al., 2015; Hartmann et al., 2009) to excellent (Hartmann et al., 2009; Davis et al., 2017). Our current findings demonstrated that the anchored system improved reliability substantially (ICC = 0.825 interrater reliability, ICC = 0.908 intra-rater reliability), surpassing benchmarks established in previous studies. The use of an anchored system in these settings could help prevent underestimating or overestimating strength of the plantarflexor group, leading to better-targeted interventions for patients recovering from injuries such as Achilles tendon ruptures or for athletes undergoing performance assessments.

Anchored method also demonstrated notable improvements in reliability for neck strength measurements compared to hand-held dynamometry. Neck extension achieved excellent ranking for both intrarater & interrater reliability (ICC > 0.90) with the anchored method, compared to the good ranking from the hand-held method (ICC < 0.90). The anchored system also had borderline excellent intra-rater and interrater reliability (ICCs = 0.889) for the neck flexion assessment. These findings align with prior research assessing the reliability of neck strength measurements with hand-held dynamometry (Shahidi et al., 2012; Cibulka et al., 2017). By reducing variability through stabilization, the anchored system offers a clinically meaningful advantage for evaluating neck strength, particularly in contexts such as cervical spine, assessment, rehabilitation and ergonomics. The results overall emphasize the critical role of external stabilization in gathering more reliable measurements of force production, especially from stronger muscle groups where confounds from raters can have a more significant influence on results.

Knee flexion and extension presented many challenges in the anchored condition. Interrater reliability in this condition ranged from moderate to good (ICC = 0.625 for knee flexion, ICC = 0.711 for knee extension). These results contradict the higher reliability found in studies like Kelln et al. (2008), where standardized positioning and belt stabilization improved measurements. We believe part of these findings stem from the testing environment which had tiled floors which reduced friction and caused a higher prevalence of mistrials and additional repetitions through movement of the stand. Additionally, we made the choice to test both knee extension and flexion at a 90° knee joint angle to prioritize efficiency of transition between knee extension and knee flexion. This decision may have compromised reliability by putting the hamstring group (i.e., knee flexors) in a shortened position when the knee joint angle is at 90° of flexion. This limitation is established in the length-tension relationship of skeletal muscle fibres were less isometric tension will be produced by fibres in a shortened position (Gordon et al., 1966). Addressing these limitations by using non-slip surfaces for testing and optimizing anchor placement or testing angles could improve reliability further, giving clinicians more confidence in their assessments and enabling personalized rehabilitation programs.

Limitations

The small sample size (n = 12) may limit the generalizability of the findings, especially among diverse populations. Additionally, the testing environment and protocol constraints may have introduced variability. Mistrials were more common when high force was being applied in the sagittal plane (e.g., knee extension) likely due to a lack of friction between the metal base of the anchor and the tile flooring. A different surface could likely limit eliminate anchor movement during trials. Future research should evaluate larger cohorts and incorporate standardized environmental conditions.

CONCLUSION

Overall, this study demonstrates the potential reliability improvements achievable with an anchored dynamometer system compared to hand-held methods, highlighting key improvements to recording maximal volitional contractions for muscle force production. The findings positively contribute to previous research, underscoring the cruciality of stabilization in achieving consistent and accurate strength assessments, especially in larger or stronger muscle groups capable of producing greater force. Using a stable anchor as an attachment point for HHDs can minimize variability resulting from disparities between tester strength, positioning, and possibly training. Notably, these findings emphasize the use of an anchored system for performance, clinical and research applications, especially concerning robust upper limb and complex lower limb muscle actions. A more reliable method for assessing muscle strength can give professionals and researchers from various fields greater confidence in their ability to develop valid procedures. Additionally, this approach may reduce the time needed to conduct these assessments, potentially decreasing the number of errors caused by individual differences among testers. Continued exploration of methodological refinements will further enhance its utility and reliability, possibly through addressing some of the limitations.

AUTHOR CONTRIBUTIONS

Chris Rawdon: Conceptualization, study design, data collection, statistical analysis, interpretation of results, literature review, manuscript drafting/editing, and correspondence. Wayne Shell: Study design, data collection, statistical analysis, interpretation of results, literature review, manuscript drafting/editing, and correspondence. Rachel Le: Statistical analysis, interpretation of results, literature review, manuscript drafting/editing, and correspondence. Kathryn Mason: Study design, data collection, statistical analysis, interpretation of results, literature review, manuscript drafting/editing, and correspondence.

SUPPORTING AGENCIES

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL APPROVAL AND INFORMED CONSENT

All procedures were approved by the Mercer University Institutional Review Board. Informed consent was obtained from all participants prior to participation.

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DATA AVAILABILITY STATEMENT

The datasets generated and/or analysed during the current study are available from the corresponding author upon reasonable request.

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ORIGINAL ARTICLE

The effect of tactical visual scanning exercises on a number of visual abilities of deaf soccer players

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ABSTRACT

The present study aimed at revealing the differences in a number of visual abilities between the experimental and control groups in the post-test. The researchers used the experimental method, and the experiment has been implemented on a sample of (20) advanced players from the National Paralympic Committee in Nineveh. They have been divided into two groups, with (10) players for each group. The research procedures includes designing tactical visual scanning exercises, which have been applied to the experimental group. The experimental group carries out the tactical visual scanning exercises, while the control group carries out the curriculum has been prepared by the team coach. The implementation of the experiment takes (8) weeks, with (3) training units per week. After that, the researchers conduct visual ability tests after the experiment ended on the two research groups, using the same procedures and steps followed in the pre-tests. The data have been statistically processed using SPSS to obtain the mean, standard deviation, percentage, t-test for related samples, t-test for independent samples, Shapiro test for normal distribution, Levene's test for homogeneity, Eta Squared test to determine the effect size for independent samples, and Cohen's d test to determine the effect size for related samples. The most notable results are that the visual scanning exercises performed by the experimental group improved all visual abilities, as demonstrated by comparing the pre- and post-test results of all abilities of the experimental group players.

Keywords: Sport medicine, Optical surveillance, Hearing impaired, Visual variables.

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INTRODUCTION

Sports for the disabled is one of the sports that seeks to achieve raising the capabilities of the disabled individual and his physical and intellectual potential, and to refine and prepare his personality and rehabilitate him in a way that ensures his correct educational preparation. It is the means through which the disabled individual can get closer and integrated in the society, to eliminate the state of isolation and seclusion that he encounters as a result of his disability. Therefore, the process of rehabilitating the disabled in sports is a phenomenon that expresses the developed society, and an awareness of the responsibility of the importance of caring for this social segment, to play its positive role in the sports field. Jordet (2020) notes that tactical visual scanning is the process by which players move their heads to monitor their surroundings during a match, detecting the positions of teammates, opponents, and empty spaces. This helps them make better tactical decisions before receiving the ball or during critical moments. This behavior is considered as part of visual perceptual skills that enhance situational awareness and reduce opposing pressure (Jordet, 2020).

In parallel, the integration of cognitive and perceptual training within sports, especially for athletes with disabilities, has garnered increasing attention in recent years. For instance, Jordet highlights that tactical visual scanning—the systematic head movements to monitor the surrounding environment—is a key factor in tactical awareness. This scanning behavior allows athletes to perceive the positions of teammates, opponents, and open spaces, thereby enhancing decision-making under pressure (Jordet, 2020). While McGuckian, et al., 2018, indicate that visual abilities are the cognitive skills associated with processing visual information during a game, such as tracking the movement of the ball and players, estimating distances, detecting gaps, and predicting opponents' movements. These abilities include peripheral vision, rapid visual focus, and quick decision-making based on visual input, which contribute to improving players' tactical and technical performance (McGuckian, et al., 2018). Similarly, McGuckian et al. emphasize the importance of visual cognitive skills in sports performance. These include abilities such as peripheral vision, depth perception, anticipation of opponents' moves, and dynamic visual acuity, all of which contribute to effective gameplay and technical execution (McGuckian and Pepping, 2018). Sports for individuals with disabilities represent a vital domain that seeks not only to enhance the physical and intellectual capabilities of disabled persons but also to provide a structured platform for personal development, social integration, and psychological rehabilitation.

Through regular physical activity and organized competition, individuals with disabilities are afforded the opportunity to overcome the constraints imposed by their impairments and to express themselves in ways that foster confidence, autonomy, and social belonging. This approach aligns with the modern societal values of inclusivity and equal opportunity, as sport becomes a vehicle for breaking the isolation and marginalization commonly experienced by disabled populations (Winnick and Porretta, 2016) (DePauw and Gavron, 2005). Inclusive sports play a transformative role in improving the quality of life of participants by strengthening motor skills, enhancing cognitive function, and promoting emotional resilience. As noted by DePauw and Gavron, sport participation supports the reconstruction of identity for individuals with disabilities and reinforces a sense of normalcy through structured physical engagement (Bailey, 2006). Moreover, sport serves as an educational medium, reinforcing discipline, teamwork, and perseverance—qualities essential for successful integration into broader society (Block and Obrusnikova, 2007). For disabled athletes, training these cognitive-perceptual functions becomes even more critical to compensate for potential sensory or motor limitations and to enhance competitive functionality (Wilson and Vine, 2017). Therefore, promoting and supporting sports for the disabled is not merely a humanitarian gesture but a reflection of a progressive and equitable society—one that acknowledges and leverages the potential of every individual, regardless of physical or cognitive differences.

MATERIALS AND METHODS

Choosing an experimental design is essential in every experimental research. It is a procedure that provides the researcher with the means to reach the desired results. Therefore, the researcher uses the experimental design called "*pre-post experiment on an experimental group and a control group*". (Al-Shafi'i and Morsi,1999).

Participants

The research sample is intentionally selected from the Nineveh Sub-Paralympic Committee players for deaf football, numbering (20) players, who represent (13.8%) of the research community. The sample has been divided into two groups (experimental and control) randomly using (lottery), with (10) players for each group. Homogeneity has been achieved for the research sample in the variables (age, height, mass, training age), and all selected visual abilities, using (Levene's Test), and Table 1 shows this.

Table 1. Values of Levene's and significance tests in the anthropometric measurements and visual abilities of the two research groups.

No	Variables	Unit of Measurement	L-T	Sig
1	Length	Cm	1.141	.300
2	Age	Years	0.230	.637
3	Training Age	Years	0.527	.477
4	Mass	Kg	3.505	.078
5	Visual Tracking	Score	0.330	.573
6	Peripheral Vision	Score	0.563	.463

It is clear from Table 1 that the significative values of the (Levene's) test for the research variables approached between (0.078-0.637) and are greater than the significance level (.05), which indicates the homogeneity of the research sample.

Equivalence has been achieved between the experimental and control research groups in the selected visual abilities, as shown in Table 2.

Table 2. The arithmetic means, standard deviations, calculated t values, and significative values for the equivalence of visual abilities between the two research groups.

No	Variables	Experimental group		Control group		t-value	Sig
		Mean	Deviation	Mean	Deviation		
1	Visual Tracking	6.300	1.494	6.700	1.337	- 0.631	.536
2	Peripheral Vision	5.500	1.354	6.300	1.059	- 1.472	.158

It is clear from Table 2 that the calculated (t) values are limited to ([1.472-]-[0.631-]) and by noting the significative values, which are limited to (0.158 - 0.536), all of them are greater than the significance level (.05), which indicates the absence of significant differences between the two research groups in visual abilities in the game of football for the deaf.

Visual abilities tests

In order to determine the tests for the research variables under study, represented by (visual tracking, peripheral vision), the researchers analyze the content of scientific sources and then presents the tests to a number of experts in the field of motor learning, measurement and evaluation and a number of soccer experts. The tests that obtained an agreement rate of (75%) has been approved, as (Bloom et al.) indicate

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that "*the researcher must obtain an agreement rate of (75%) or more from the opinions of the arbitrators*" (Bloom et al., 1983). The visual tracking test has also been adopted, with the subject standing 3 meters behind a wooden wall, facing the ball. A colleague rolls the ball 5 meters from the top of the wooden wall toward the subject, ensuring the ball passes over the wall. The subject determines the color of the sticker placed on the ball before it crosses the 3 meters, as there are five different colors for the ball. Scoring: Each subject is given ten attempts. A score of 1 is awarded for determining only the color of the sticker. The minimum score is 0 and the maximum score is 10 in the test. Figure 1 illustrates the visual tracking test.

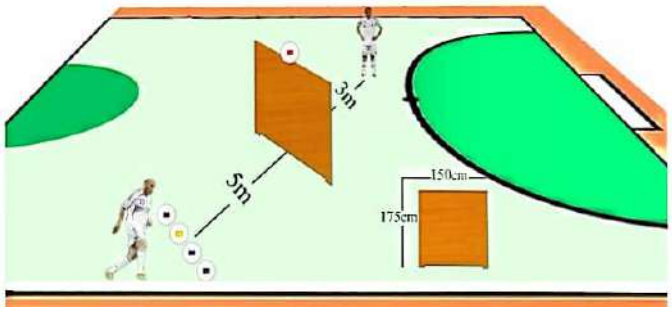

Figure 1. Visual tracking test.

For the peripheral vision test, the teacher and the subject standing in front of them continuously pass a ball over a distance of 8 meters. Fellow students standing 4 meters behind the subject make continuous passes with balls of different colors, with the distance between each student being 20 meters. The teacher gives instructions to the student standing in front of them to identify the color of the ball being passed between the students standing behind the subject. Scoring method: Each student is given ten attempts. A score of one is awarded for identifying the correct color only. The minimum score is zero and the maximum score is 10 in the test. (Al-Mutawaki, 2018), Figure 2 shows a peripheral vision test.

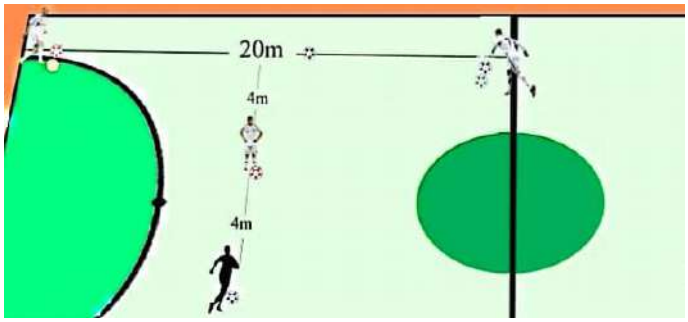

Figure 2. A peripheral vision test.

Training methods

The repetitive training method has been used in implementing the schematic visual scanning exercises. The schematic visual scanning exercises are applied in the main section of each training unit, specifically in the schematic aspect. The implementation of the schematic visual scanning exercises takes (8) weeks, with two intermediate cycles, and each intermediate cycle contains (4) minor cycles (weeks). Each minor cycle contains (3) training units per week, thus the total number of training units is (24) training units. The load movement oscillates in each intermediate cycle (1:3). The training units are conducted on (Sunday, Tuesday, Thursday) of each week at the Al-Mustaqbal Al-Mashreq Sports Club field.

The intensity (competitive intensity) of the visual scanning exercises was used. Positive rest has been used between repetitions and exercises. The number of repetitions is determined based on theoretical frameworks, as well as pilot experiments. The rest periods between repetitions, between sets, and between exercises are determined based on theoretical frameworks, as well as pilot experiments, by resting the heart rate to (100-110 bpm) between repetitions and (90 bpm) between sets and exercises. A Viatom-Checkme O_2 wristwatch and a pulse oxmeter are used to measure heart rate between repetitions, sets, and exercises. The exercise areas used in the research are determined inside the stadium according to what is indicated by (Labsy et al, 2014) and (Clemente, 2016) in a way that is consistent with the tactical situations according to the studies (Sporis et al, 2009), (Clemente, 2016) and (Hill-Haas et al, 2011). Both the size and the rest periods are fixed, and the change in the difficulty of performance was through reducing the specific areas if the largest area is used according to the number of players and then reducing these areas to increase the difficulty of performance (intensity) according to what has been indicated by both (Clemente, 2016, 86) and (Owen, et al, 2012, 51) as follows:

Table 3. The field sizes (width x length) (meters) used for the visual planning scanning exercises (Clemente, 2016, 86) and (Owen, et al, 2012, 51).

Stadium size	1 VS 1	2 VS 2	3 VS 3	4 VS 4	5 VS 5	6 VS 6
Small	5 VS 10	10 VS 15	15 VS 20	20 VS 25	25 VS 30	30 VS 35
Middle	10 VS 15	15 VS 20	20 VS 25	25 VS 30	30 VS 35	35 VS 40
Large	15 VS 20	20 VS 25	25 VS 30	30 VS 35	35 VS 40	40 VS 45

The researchers designed a number of exercises used to develop visual abilities. These exercises were applied to the experimental group and are withheld from the control group, as the control group used regular exercises designed by the trainer. The researchers are able to design 9 exercises for schematic visual scanning. Figure 3 show examples of one of the schematic visual scanning exercises that were designed. The objective of this exercise is to develop tactical visual scanning. A number of tools are used, such as footballs, colored jerseys, colored flags, and colored goals. The playing area and its dimensions: the attacking zone (30m x 35m). How to perform the exercise: Play (5x3) with (2) balls in the designated area. The team in possession of the balls consists of five players within the designated area, each with (2) balls. The team in possession of the balls takes possession during the specified time of the exercise. During the exercise, the players visually scan their teammates within the designated area and the coach to ensure the correct transfer of the ball. During the exercise, the coach raises one of the colored flags at the appropriate moment of his choice, allowing the team in possession to score on the goal according to the color specified by the coach. The exercise continues, with the positions being changed with each repetition. Each correct goal is awarded a point to the team. Two balls are used during each exercise.

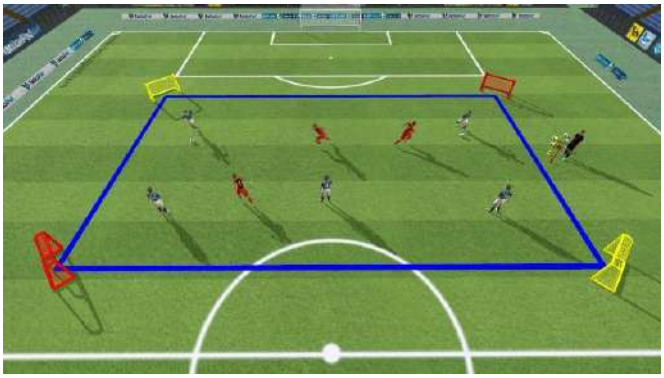

Figure 3. Examples of one of the schematic visual scanning exercises that were designed.

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Figure 4 shows another visual development exercise, designed earlier. It differs from the previous exercise in terms of the playing area and zone. Equipment used: footballs, colored shirts, colored flags, colored rings. Playing area: center zone (30m x 35m). Method of exercise: Play (4x4+3) in the designated zone. The team in possession of the ball consists of four players inside the designated zone and three support players. The team in possession receives the ball during the allotted time of the exercise. During the exercise, the players visually check their teammates inside the designated zone, the support players, and the coach to ensure correct passing of the ball. During the exercise, the coach raises one of the colored flags at the appropriate moment of their choice, allowing the player in possession of the ball to pass it into the designated zone according to the color assigned by the coach. At the same time, the players visually check the coach to move to the zone to which the ball is being passed. The exercise continues, changing positions with each repetition.

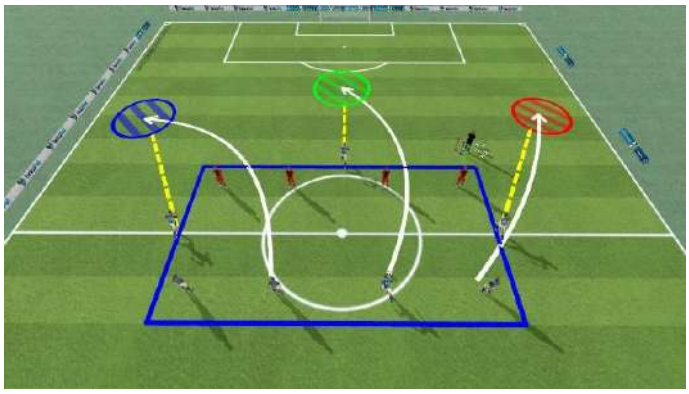

Figure 4. Examples of one of the schematic visual scanning exercises that were designed.

Statistical analysis

Statistical methods have been extracted using the SPSS statistical package, which included:

- Percentage.
- Arithmetic mean.
- Standard deviation.
- Shapiro test for normal distribution.
- Levene's test for homogeneity.
- t-test for independent samples.
- t-test for related samples.
- Eta squared test to determine the effect size for independent samples.
- Cohen's d test to determine the effect size for related samples.

RESULTS

Table 4. Arithmetic means, standard deviations, calculated t values, significance, and effect size (Cohen's d) for the pre- and post-tests of visual abilities for the experimental group.

No	Statistical parameters variables	Unit of measure	Pre-test		Post-test		(T) calculated	Sig.	Effect size	Std
			Mean	Deviation	Mean	Deviation				
1	Visual Tracking	Score	6.300	1.494	9.400	0.843	-5.670	.000	1.79	Large
2	Peripheral Vision	Score	5.500	1.354	9.100	0.737	-6.409	.000	2.02	Large

Table 4 shows that there are significant differences between the averages of the pre- and post-tests in the visual ability tests for the experimental group, as the significative values reached (.000/.000), respectively, which is smaller than the significance level (.05), and the value of the effect size (Cohen's d) was (1.79/2.02), respectively, indicating a large effect size in favor of the post-test.

Table 5. Arithmetic means, standard deviations, calculated t values, significance, and effect size (Cohen's d) for the pre- and post-visual ability tests for the control group.

No	Statistical parameters variables	Unit of measure	Pre-test		Post-test		(T) calculated	Sig.	Effect Ssze	Std
			Mean	Deviation	Mean	Deviation				
1	Visual Tracking	Score	6.700	1.337	8.400	0.699	- 4.295	.002	1.35	Large
2	Peripheral Vision	Score	6.300	1.059	8.000	1.247	- 3.285	.009	1.03	Large

Table 5 shows that there are important differences between the averages of the pre- and post-tests in the following visual ability tests (visual tracking, peripheral vision) for the control group. The significative values reached (.002/.009), respectively, which are smaller than the significance level (.05). The effect size value (Cohen's d) is (1.35/1.03), respectively, indicating a large effect size in favor of the post-test.

Table 6. Arithmetic means, standard deviations, calculated t values, significance, and effect size (Eta squared) for the post-tests of visual abilities for the experimental and control groups.

No	Statistical parameters variables	Unit of measure	Experimental group		Control group		(T) calculated	Sig.	Effect size	Std
			Mean	Deviation	Mean	Deviation				
1	Visual Tracking	Score	9.400	0.843	8.400	0.699	2.887	.010	0.316	Large
2	Peripheral Vision	Score	9.100	0.737	8.000	1.247	2.400	.027	0.242	Large

Table 6 shows that there are outstanding differences between the averages of the two post-tests in the visual ability tests for the experimental and control groups. The significative values are (.010/.007), respectively, all of which were smaller than the significance level (.05). The effect size values (Eta squared) are (0.316/0.340), respectively, indicating a large effect size in favor of the experimental group.

DISCUSSION

The researchers attribute the development in the results of visual abilities in Tables (4)(5)(6), which indicates the development of the experimental group players in visual abilities, as well as the superiority of the experimental group players over the control group players in all visual abilities, to the effective positive effects of the tactical visual scanning exercises. The researchers attribute the development in peripheral vision to the tactical visual scanning exercises, as the results that appeared for peripheral vision in the pre- and post-test of the experimental group indicate the presence of significant differences, indicating a significant improvement that can be explained by the ability of the tactical visual scanning exercises to improve peripheral vision in deaf soccer players, who are in dire need of this visual ability due to the absence of their sense of hearing. This is consistent with what (Al-Zamli) indicated, that there is a direct relationship between offensive and defensive abilities and sports visual vision.

The researcher attributes the reason for this to the fact that this skill (peripheral vision) is used when the player is in influential positions that contribute to uncovering the field and creating gaps in the opponent's defense. The correct vision of the playmaker player is the real key to team play, as it enables the attacking team to continue the control of the largest possible area of the field, the team also enables it to optimally

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exploit gaps in the opposing defense. Long passes are often used for escaping attacking players, often behind defenders. Given the significant developments in modern football, the team with the best and fastest ability to spread out is the most dangerous to the opposing team's goal (Al-Zamli, 2012). Donald & Caroline assert that vision is the primary sense used to obtain information from our environment, and that it is important for distinguishing between sight and sports-related vision. Visual training provides the brain with information from other senses (the corresponding internal senses) and improves the body's motor systems (neuromuscular) for output (response) (Donald & Caroline, 1995). Fleh's study demonstrates the importance of peripheral vision exercises as effective tools for developing the visual abilities of deaf football players and enhancing their peripheral vision. This training revolves around creating training situations that simulate match conditions, in which players are exposed to multifaceted visual stimuli, increasing their awareness of the positions of teammates, opponents, and the empty spaces around them.

The use of these methods has been shown to improve the spatial perception and expand the peripheral vision, which positively impacts the team's tactical performance by enhancing the speed of reading the scene and making decisions. The study also confirms that these exercises provide an effective solution to compensate for the deficient visual sense resulting from hearing impairment, helping deaf players acquire visual tactics that are reflected in their better ball control and movement on the field (Fleh, 2021). The researchers attribute the development in visual tracking to the tactical visual scanning exercises, as these exercises included tracking the ball's movements and the color of the flag raised by the coach so that the player could choose the target that matches the color of the raised flag. The results that appeared for visual tracking in the pre- and post-test for the experimental group indicate the presence of impressive differences in favor of the post-test, in addition to the superiority of the players of the experimental group that used the tactical visual scanning exercises over the players of the control group in the post-tests in visual tracking. This is consistent with (Al-Zamli), that the process of tracking the ball for the defender or the attacker is a necessary matter, and that the limited level of vision will lead the players to make incorrect decisions capable of creating surprising positive circumstances. It is also characterized by the classic form, which distinguishes it by being exposed to the opponent and free of surprise. (Al-Zamli, 2012).

The researchers also believe that structured visual training contributes effectively to improving the visual tracking skills of deaf soccer players, which enhances their ability to follow the ball, interact with it, and assess the positions of the players around them, despite limited hearing. This is confirmed by a study that included an age group (12–14 years). The researchers used an experimental model that included an experimental and control sample, during which they applied specialized visual exercises – including visual scanning and tracking in training situations that simulated a competitive context. This shows a primordial improvement in the experimental group compared to the control group, as it shows an obvious improvement in the accuracy and speed of visual tracking – and this is attributed to the scanning exercises that forced the players to follow the ball and the movement of the players using visual filing (Ben Zidane, et, al, 2020).

The experiences of researchers in this field confirm the existence of a close relationship between the level of comprehensive vision and technical and tactical ability. A large percentage of players who possess a broad and comprehensive vision are those who possess field intelligence and high technical ability. Furthermore, the type of game has an impact on the level and breadth of vision. Experiments conducted in the former Soviet Union confirm that football, basketball, handball, boxing, wrestling, and weightlifting players possess a high level of comprehensive vision (Jaber et al., 1991).

The characteristics of fatigue and the variables present require developing the lateral vision of players, especially since there are kinetic variables occurring within a single moment. They also require developing

the level of ball tracking, the depth of vision, and the required shape. Therefore, when the ball is at or below eye level, directing the ball toward the goal and scoring a goal will not be as intended. This indicates the addition of attributes to attackers from the moment the attacker receives the ball and handles it on the field through several stages, including:

1- Knowledge of the ball's flight and the accuracy of its arrival.
2- The best way for a player to receive the ball. (Al-Zamli, 2012).

CONCLUSIONS AND RECOMMENDATIONS

In light of the results obtained, the researchers reach the following conclusions:

- The visual scanning exercises implemented by the experimental group resulted in positive development in all visual abilities.
- The curriculum prepared by the trainer and implemented by the control group resulted in positive development in all visual abilities.
- The experimental group, which used the visual scanning exercises, outperformed the control group in all visual abilities.

After examining the findings, the researchers make the following set of recommendations:

- The need to emphasize the tactical visual scanning exercises by deaf football coaches, given the research results' positive improvement in the visual abilities of deaf football players.
- Emphasis should be placed on using the repetitive training method in tactical visual scanning exercises, as this allows the coach to better control the components of the training load.
- The possibility of conducting similar research on other age groups and genders in deaf football, as well as conducting similar studies on other team sports.

AUTHOR CONTRIBUTIONS

Yonis initiated the idea, supervised the research, and evaluated and edited the research paper. Basher wrote the first draft, documented the training methods, and Yonis provided the training materials and assisted Basher in analysing the results. The authors contributed to drafting the final manuscript and discussing the findings.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

How pacing patterns influence middle-distance performance: Perspectives from object tracking and oxygen uptake

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ABSTRACT

This study explores the impact of kinematic and physiological factors on middle-distance running performance to optimize training strategies. Six runners participated in experiments with three pacing patterns (F-S, Even, and S-F), monitored using a drone, camera, and tracking technology. VO_2master measured oxygen uptake, and post-race PBLa and RPE were assessed. Results showed that the Even pattern had the lowest speed variation and most consistent trajectory. The running distances for the three pacing patterns were similar: F-S (807.30 ± 0.88 m), Even (806.52 ± 0.66 m), and S-F (806.37 ± 1.63 m). Although the Even strategy required less work, the F-S pattern had lower oxygen uptake, indicating higher efficiency. Heart rate and oxygen uptake stabilized fastest in the Even pattern, while the F-S pattern led to the lowest blood lactate (15.0 ± 2.56 mmol/L). The Even pacing is optimal for consistent performance, while F-S may optimize energy efficiency. This study emphasizes tailoring pacing strategies to an athlete's profile, suggesting further research on personalized pacing to enhance performance.
Keywords: Sport medicine, Middle-distance running, Pacing pattern, Object tracking, Oxygen uptake.

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INTRODUCTION

The primary objective of pacing studies is to determine an optimal strategy that ensures both the physiological well-being of athletes and exceptional race results. However, various external factors affect performance, and the human body's involvement in sports is highly complex. Consequently, the search for an ideal pacing strategy is still in its early stages, focusing primarily on energy metabolism and the assessment of pace adjustments that can better harness physiological functions. Traditionally, pace analysis in middle- and long-distance running has relied on manual video tracking, where speed is evaluated at 100 m intervals (Matsuo et al., 1992; Enomoto et al., 2005,2006; Kadono et al.2008; Yang & Enomoto, 2022a,b). However, this method is labour-intensive, time-consuming, and does not provide a comprehensive race analysis, making it inefficient for modern sports performance evaluation. As a result, there has been a shift towards automatic video analysis, which integrates image processing, machine learning, and artificial intelligence (Sheng et al., 2020; Wang et al., 2019). This approach has found widespread applications in technical analysis, athlete tracking, and video monitoring.

Advancements in video-based detection and tracking methods have revolutionized sports analysis, enabling more accurate and faster assessments of competition processes. Traditionally, sports training relied heavily on subjective and empirical teaching methods, with coaches observing athletes' technical movements using the naked eye. While this provided useful insights, it was limited in accuracy and consistency. Moreover, the use of sensors for movement detection added unnecessary burdens on athletes and impacted their competitiveness (Ghasemzade & Jafari, 2010; Sheng et al., 2020). Laboratory-based measurements also fell short, as exercise machines could not fully replicate natural movements, and outdoor conditions were difficult to simulate.

With the rise of computer vision technology, non-contact human motion analysis has become possible, allowing for more practical and accurate assessments of athletic performance. Athlete tracking and recognition through video-based object detection and tracking have gained attention, especially with the growing interest in integrating digital video technology into sports training (Dearden et al., 2006; Xing et al., 2010; Lu et al., 2013; Manafifard et al., 2017). Although there has been extensive research on sports like basketball, football, volleyball, and swimming (Dearden et al., 2006; Xing et al., 2010; Lu et al., 2013; Manafifard et al., 2017; Victor et al., 2017; Suzuki et al., 2020), limited work has been done on track and field athletes. The application of drone-based technology and automatic analysis presents unique challenges in track and field events. Middle-distance races cover large areas, and the athletes are relatively small in scale, making accurate tracking difficult. However, overcoming these challenges is crucial for advancing performance analysis in middle-distance running. Drone technology, combined with advanced computer vision techniques like OpenCV, offers promising solutions for tracking middle-distance runners, determining their actual running distance, and analysing their pacing patterns in real-time.

In middle-distance running, athletes do not maintain a constant pace throughout the race. Instead, they adjust their speed based on external conditions, physiological factors, and psychological states. These adjustments lead to the formation of specific pacing patterns, which are critical to race performance. Pacing behaviours among elite athletes vary depending on the event and the individual (Casado et al., 2021). Even small variations in pacing among top runners can have a significant impact on race outcomes (De Koning et al., 1999). Previous studies have focused on analysing performance in relation to pacing strategies, particularly on the benefits of fast-start (F-S) pacing strategies (Ariyoshi et al., 1979; Jones et al., 2008). The way in which athletes distribute their energy expenditure during a race can influence factors such as the contribution from oxidative and non-oxidative metabolic pathways, fatigue development, and ultimately, race performance

itself (Foster et al., 1994). However, relatively few studies have explored how specific pacing strategies directly influence performance, especially in real-world track settings.

Most past research on middle-distance pacing has been confined to laboratory settings or single pacing pattern studies on the track. This study proposes a more dynamic approach by utilizing drone technology to capture race videos of middle-distance runners, followed by automatic video analysis using OpenCV. By tracking runners in real-time, this method can calculate their actual coordinates, running distance, and speed with higher precision. The integration of drone-based tracking in this study aims to provide a more detailed understanding of pacing patterns and their impact on performance. Tracking middle-distance runners using drone footage offers valuable insights into pacing strategies and performance analysis. This study addresses the limitations of traditional manual analysis by leveraging advanced video-based detection methods, enabling more accurate and efficient performance assessments. By investigating multiple pacing patterns and their physiological and biomechanical effects, this research contributes to the growing body of knowledge on optimal pacing strategies in middle-distance running.

METHODOLOGY

Participants

Six healthy male endurance athletes (1500 m runners) [20.5 ± 0.76 years; 1.74 ± 0.06 m in height; Weight: 62.1 ± 8.23 kg; Body fat percentage (%):9.32 ± 2.16; Resting blood lactate concentration (BLa): 1.5 ± 0.31mmol/L; Maximal oxygen uptake:62.07 ± 1.62ml/kg/min; Maximum heart rate:186.67 ± 5.34bpm; Personal best record for running 1500 m(PB): 239.99 ± 5.14 s] volunteered and gave written informed consent to participate in this study. This study was approved by the University of Tsukuba ethics committee (体023-104). All participants were professional middle-distance runners at the University of Tsukuba (see Table 1 for details).

Table 1. Characteristics of participants.

No.	Age (year)	Height (m)	Weight (kg)	Body fat percentage (%)	Bla (mmol/L)	$\dot{V}O_{2max}$ (ml/kg/min)	Hr_{max} (bpm)	PB1500 (s)
1	20	1.60	49.7	6.4	1.3	62.3	183	240.50
2	22	1.80	62.9	8.7	1.5	58.9	190	240.74
3	20	1.73	58.5	9.0	1.1	63.4	180	238.65
4	20	1.80	63.9	9.6	1.2	61.2	195	240.20
5	21	1.81	77.3	13.6	2.0	63.4	182	231.09
6	20	1.72	60.0	8.6	1.7	63.2	190	248.74
Mean	20.50	1.74	62.10	9.32	1.47	62.07	186.67	239.99
SD	0.76	0.07	8.23	2.16	0.31	1.62	5.34	5.14

Experimental design

This experiment was conducted on a standard 400 m track and field ground, with each athlete completing three 800 m pace runs (Pace is determined based on their 1500 m running speed.). Prior to the experiment, athletes received a detailed explanation of the procedures and were required to sign a consent form indicating their agreement and understanding of the experimental procedures. Three patterns of pace were set: Fast-Slow pacing pattern (F-S: The first 400 m is fast, and the last 400 m is slow), Even pacing pattern, and Slow-Fast pacing pattern (S-F: The first 400 m is slow, and the last 400 m is fast), with speed controlled by transmitting sound every 50 m. Running speeds were determined in consultation with the athletes, and the order of the runs was randomized. During the runs, athletes were equipped with a portable expired gas

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analyser (VO_2master MW-1100, Canada) to measure dynamic oxygen uptake changes during exercise. A Polar heart rate sensor (H10, Finland) to monitor heart rate fluctuations. After each run, the lactate value was measured, and the RPE value (rate of perceived exertion) was recorded. Peak blood lactate concentration (PBLa) was measured using fingertip blood collection (Lactate Pro 2; Japan; measurement range 0.5-25.0 mmol/L; measurement time 15 seconds). Blood collection occurred at 1, 3, and 5-minute intervals after the race until the runner's blood lactate concentration began to decrease. The interval between test runs was at least 30 minutes, with lactate testing conducted before each test run. We decided that the lactate concentration should be less than 4 mmol/L before the next test run. Athletes' feedback was considered, and if they felt able, they proceeded with the next test run even if the lactate concentration was over 4 mmol/L. At the same time, we recorded all the test runs on video. To track the coordinates of the runners and calculate the actual distance and real-time changing speed of the run, we used a drone (MAVIC3-CLASSIC, DJI, China) to capture the motion process of all contestants (4K,29.97fps). The drone flight was authorized by Japan's Ministry of Land, Infrastructure, Transport and Tourism (東空運航第27987号), as well as the University of Tsukuba (第23.24号). Additionally, a single digital video camera (HC-VX908M, Panasonic, Japan) was positioned at the top of a building beside the track, with panning to follow the runners. The camera recorded at a speed of 59.94 fps, saving the footage in MP4 format. We marked the track every 50 m in advance. The frame size was analysed by video analysis software to calculate the elapsed time and average running speed at 50 m sections (Figure 1).

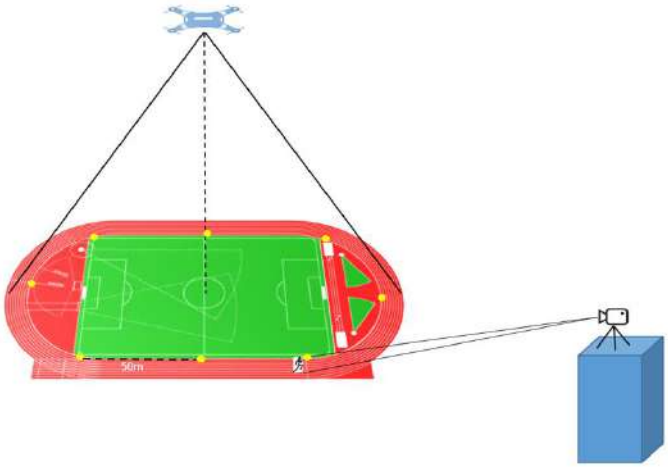

Figure 1. Drone and camera photography diagram.

Tracking algorithm, coordinate calibration and data calculation and processing

In this study, we utilized the Correlation Single-Object Tracking (CSRT) algorithm to track runners in drone footage. The CSRT tracker was chosen due to its high accuracy and its capability to track small targets in high-definition videos. It demonstrated strong performance across various target types, motion patterns, and image backgrounds. The CSRT algorithm operates by using a template to represent the target being tracked. In each frame, the tracker applies correlation filtering to identify regions matching the template and determines the best-matching region as the target's current position. The template is updated dynamically to reflect changes in the target's appearance. The CSRT algorithm employs a discriminative correlation filter framework, designed to distinguish between the target object and the background. In previous work, we successfully tracked 1500 m runners during a competition (Yang et al., 2023). We enhanced the original algorithm to improve tracking performance and accurately output image coordinates. Figure 2 demonstrates the tracking results.

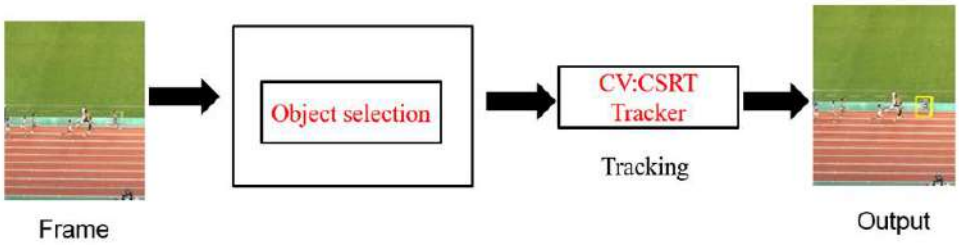

Figure 2. Structure of the object tracking method.

Figure 3. The effect of detecting and tracking a runner from drone video, and Image points for calibration.

For image calibration, we surveyed the track and field grounds prior to the running to determine precise coordinates. AutoCAD was employed to draft the track layout and measure coordinates (Yang et al., 2023). The track was a standard 400 m oval with eight lanes. The two semicircles had a radius of 37.9 m, while the straight sections measured 80 m in length and 75.8 m in width. The outer edge of the starting line for lane eight of the 110 m hurdles served as the origin point (0, 0) (Figure 3). For image-to-actual coordinate calibration, we selected 13 specific points on the track (shown in Table 2, Figure 3) and applied the Direct Linear Transformation (DLT) method to align the image coordinates with real-world coordinates. Regarding the calculation of position coordinates, the 2D DLT method (Walton, 1981) was employed. This technique establishes the relationship between image coordinates and real-world coordinates, allowing for accurate positioning of points on a 2D plane from camera images. The process involves two key steps: (1) calibration using multiple reference points (with known positions) to determine the camera's internal and external parameters, and (2) coordinate transformation, wherein DLT equations are constructed based on the 2D pixel coordinates of the reference points and their corresponding real-world coordinates. The DLT equations are then solved to derive transformation coefficients (DLT coefficients), which are subsequently used to calculate the 2D coordinates of unknown points on the image (Walton, 1981; Abdel-Aziz et al., 2015).

To reduce noise in the data, we first reduced the video frame rate from 29.97 fps to 14.99 fps, followed by data smoothing. To further refine the accuracy of the tracked data, we applied a Butterworth low-pass filter (MATLAB) with a cutoff frequency of 3 Hz to remove high-frequency noise (Winter et al., 1974). With this precise correction of coordinates, we accurately calculated the athletes' running distances and speeds,

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providing reliable measurements. This comprehensive approach significantly improves both the accuracy of the tracking system and the quality of data analysis in sports performance research.

Table 2. Corresponding points between image and actual coordinates.

Points	Actual points		Image points	
	X-coordinate	Y-coordinate	X-coordinate	Y-coordinate
1	110	9.76	2678	1928
2	147.77	44.54	3444	1202
3	129.2	80.3	3105	432
4	110	85.56	2723	301
5	80	85.56	2080	268
6	40	85.56	1424	250
7	30	85.56	1010	250
8	-7.9	48.07	275	1027
9	-2.8	28.68	357	1427
10	20.2	11.08	778	1823
11	30	9.76	968	1865
12	60	9.76	1595	1909
13	100	9.76	2461	1930

Note. The table illustrates the calibration of coordinate points for a video capturing a runner finishing a race. While the actual coordinates remain fixed, the image coordinates need to be extracted from each captured video frame.

Calculation of running speed and distance

To calculate the actual running distance, we used the following formula (Equation 1), based on the calibrated coordinates:

$$D = \sqrt{(x_n - x_{n-1})^2 + (y_n - y_{n-1})^2} \quad \text{..... (Equation 1)}$$

Here, D represents the distance between two points, and x_n and y_n are the coordinates at different times n and n-1.

The runner's speed can be calculated using the following formula (Equation 2):

$$v = \sqrt{v_x^2 + v_y^2} \quad \text{..... (Equation 2)}$$

Where:

$v_x = (x_n - x_{n-1}) * 14.99\text{fps},$

$v_y = (y_n - y_{n-1}) * 14.99\text{fps}.$

In this calculation: v_x and v_y represent the horizontal and vertical speed components, respectively.

v is the total speed of the runner. By using these equations, we can accurately measure both the distance covered and the speed of the runner in each video frame.

Using kinetic energy to calculate power. We can use kinetic energy divided by time to calculate instantaneous power. Power is defined as the rate at which energy changes over time, and the rate of change in kinetic energy can represent power.

To calculate instantaneous power, over a short time interval, we can use the change in kinetic energy:

$$P = \frac{\Delta KE}{\Delta t} = \frac{\frac{1}{2}m\left(v_f^2 - v_i^2\right)}{\Delta t} \text{.....(Equation 3)}$$

Where:
P is the power; ΔKE is the change in kinetic energy; Δt is the time interval; v_f is the velocity at the end of the time interval; v_i is the velocity at the beginning of the time interval.

For *n* speeds, the total speed variation *Δv*, calculated using the absolute values of all adjacent speed changes, can be expressed as:

$$\Delta v = \sum_{i=1}^{n-1} |v_{i+1} - v_i| \text{..... (Equation 4)}$$

Here, $v_1, v_2, \ldots, v_n$ are the *n* speeds. This formula represents the sum of the absolute values of the differences between each pair of adjacent speeds.

Statistical analysis

This study used SPSS and Excel for statistical analysis. Results are presented as mean ± standard deviation (±SD). The Shapiro-Wilk test was used to assess normality, and homogeneity of variance was tested. For data meeting normality and homogeneity assumptions, one-way ANOVA was conducted, followed by LSD post hoc tests if significant differences ($p < .05$) were found. For non-normal data or unequal variances, the Mann-Whitney U test was applied. The significance level was set at .05.

RESULTS

Figure 4 shows the image coordinates (top, black lines) obtained from tracking the videos of a runner during three different-paced 800 m runs (Fast-Slow: F-S; Even; Slow-Fast: S-F) taken by a drone and the actual tracking coordinates (bottom, grey lines) calibrated from the image coordinates. We output the image coordinates of the six runners, calibrated these coordinates, and then obtained the actual running coordinates of the runners. This allowed us to calculate their running speed and distance. In our calculations of the coordinates output after tracking six runners, we found the distances for three different 800 m pacing patterns to be as follows: the F-S pacing pattern at 807.30 ± 0.88 m, the Even pacing pattern at 806.52 ± 0.66 m, and the S-F pacing pattern at 806.37 ± 1.63 m, with the distance for the F-S pattern being slightly shorter (Table 3). However, there were no significant differences in distances among the three pacing patterns. Therefore, regardless of the pacing pattern, the distance run by the runners is almost equal in the absence of special circumstances.

Table 3. Actual distance covered by runners at different paces after object tracking.

Runners	F-S(m)	Even(m)	S-F(m)
1	807.46	805.30	806.31
2	807.71	807.42	804.73
3	808.36	806.64	806.66
4	808.02	806.93	803.99
5	806.09	806.66	808.70
6	806.14	806.17	807.83
Mean	807.30	806.52	806.37
SD	0.88	0.66	1.63

Note. No significant difference in all groups.

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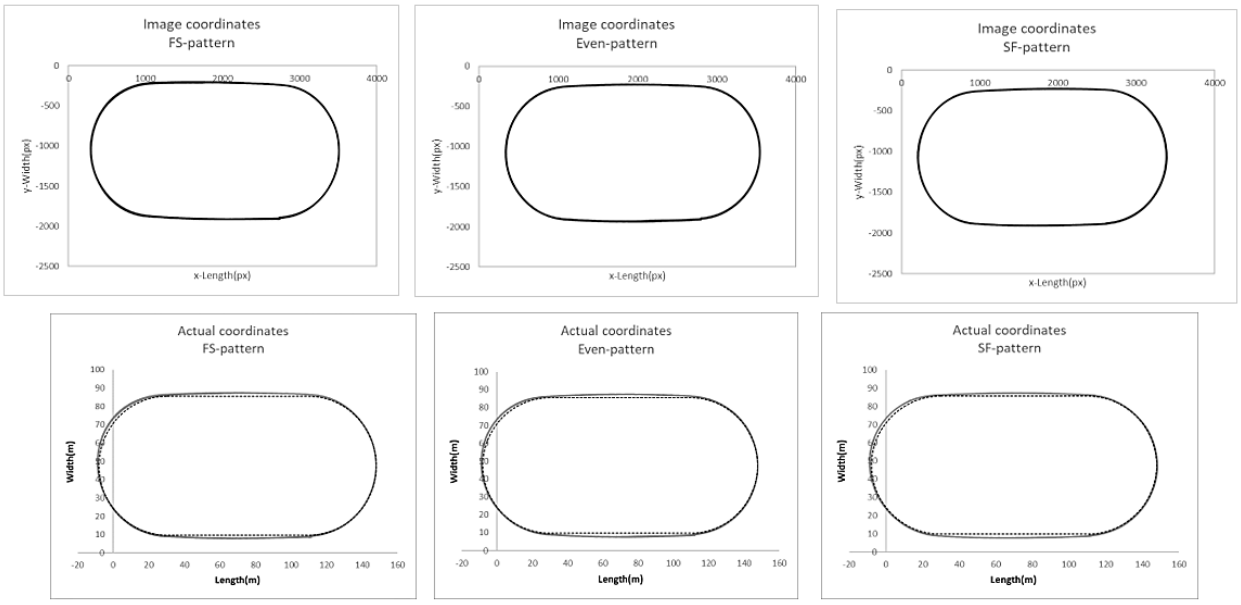

Figure 4. Tracked image coordinates of a runner (top) and actual tracked coordinates after calibration from the image coordinates (bottom). (The dotted lines represent the inner edge of the playground).

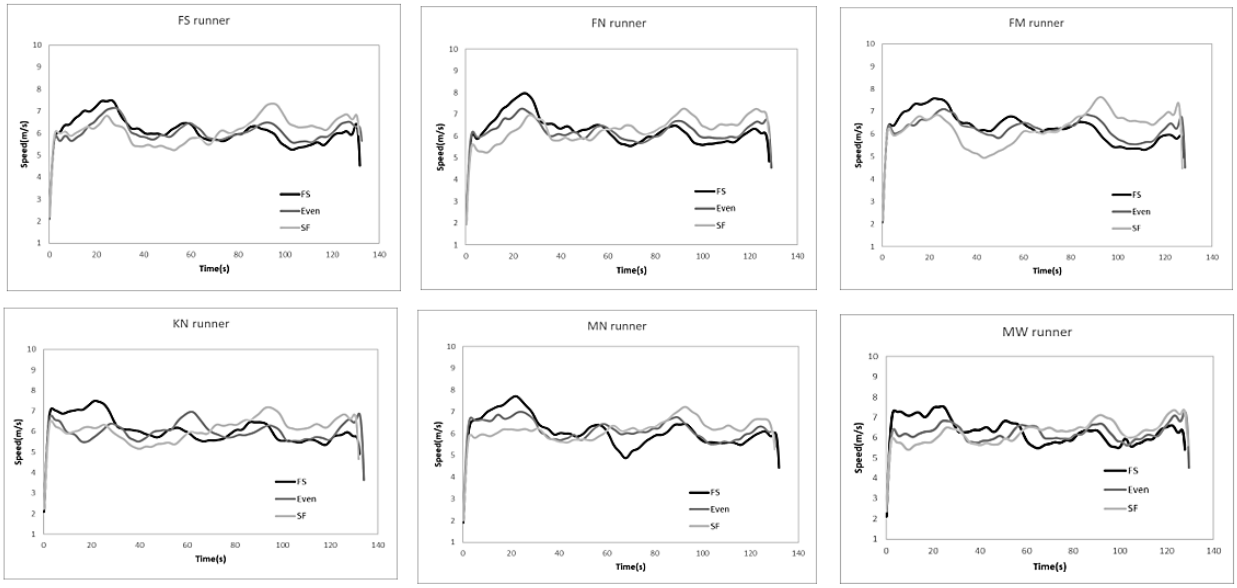

Figure 5. Changes in speed after tracking the six runners.

By tracking middle-distance runners, we can output their coordinates and subsequently calculate all speed variations. Figure 5 shows the speeds calculated from the actual coordinates of six runners after tracking their three different pacing patterns. It is evident that after an initial acceleration of 2 seconds, the speed variations display three distinct pacing patterns: F-S, Even, and S-F. In terms of acceleration, the initial acceleration of the F-S pacing pattern is significantly higher than that of the Even and S-F pacing patterns, with the F-S pacing pattern quick start pattern showing obvious acceleration deceleration. Conversely, in the S-F pacing pattern among the six runners, the acceleration of five of them is slower than that of the F-S and

Even pacing patterns. This change in acceleration and the momentary variation in speed during motion cannot be detected using traditional manual video analysis methods.

Table 4 presents the calculated total speed variations after tracking the six runners. In order to exclude the impact of acceleration and deceleration at the beginning and end on the overall data, we excluded the first 50 m and the last 50 m of the race. Among the different pacing patterns observed, the F-S pacing pattern exhibits the highest average total speed variation. The average values of the total speed variation for the Even (7.13 ± 0.54) and S-F (7.13 ± 0.72) pacing patterns are nearly identical. There is no significant difference in total speed variation among the three pacing patterns observed across the six runners.

Table 4. Total speed variation Δv for runners.

Runners	F-S	Even	S-F
1	8.41	7.29	7.12
2	8.18	6.75	5.87
3	6.43	8.00	6.52
4	6.08	6.28	7.70
5	7.55	7.03	7.67
6	7.09	7.43	7.87
Mean	7.29	7.13	7.13
SD	0.85	0.54	0.72

Note. No significant difference in all groups. In order to reduce the impact of acceleration and deceleration at the beginning and end of the race, we excluded the first 50 m and the last 50 m of data.

As per the work-energy theorem, the work done is equivalent to the change in kinetic energy. Table 5 shows that the Even pacing pattern required the least work, followed by the F-S pacing pattern, while the S-F pacing pattern required the most. Although the differences were not statistically significant, this trend suggests that the Even pacing pattern may help conserve energy and improve endurance and efficiency during a race.

Table 5. Total work calculated based on changes in running speed during the race.

Runners	F-S	Even	S-F
MW	4.408×10^3	4.414×10^3	3.900×10^3
MN	4.979×10^3	4.212×10^3	3.776×10^3
KN	4.497×10^3	4.521×10^3	4.929×10^3
FM	5.308×10^3	6.190×10^3	7.092×10^3
FN	5100×10^3	5.052×10^3	4779×10^3
FS	4.487×10^3	4.142×10^3	4.501×10^3
Mean	4.797×10^3	4.755×10^3	4.830×10^3
SD	347.21	705.98	1096.58

Note. Based on the work-energy theorem, work equals the change in kinetic energy.no significant difference in all groups.

Moreover, depending on the running speed, the dynamics of heart rate (HR) and oxygen uptake ($\dot{V}O_2$) during the running process also differ. Figure 6 illustrates the dynamic changes in speed, HR, and $\dot{V}O_2$ across different sections under various running pacing patterns. It is evident that as the initial speed accelerates, HR and $\dot{V}O_2$ in any pacing pattern exhibit an upward trend before stabilizing. Analysing the HR changes across the three different pacing patterns, the HR rise slope after acceleration is steeper for both the F-S and S-F pacing patterns, while it is relatively smaller for the Even pacing pattern. After HR stabilizes and until the end of the race, the HR of the F-S and S-F pacing patterns remains higher than that of the Even pacing pattern. During running, there was no significant difference in HR between each pacing pattern.

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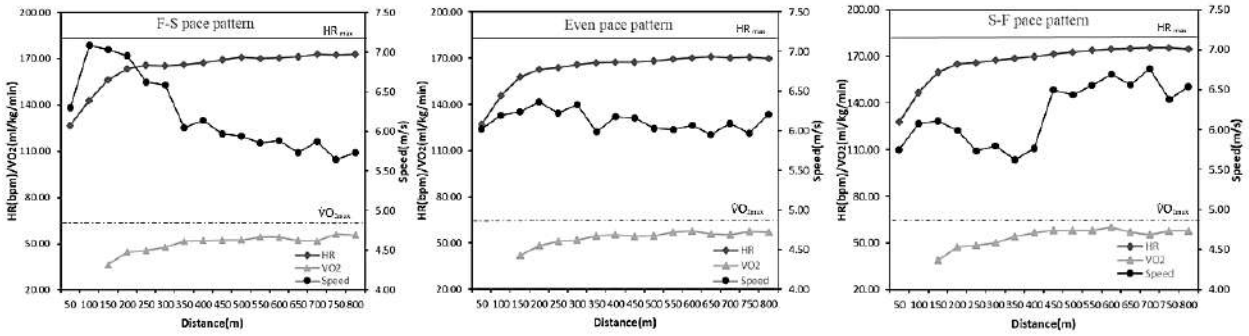

Figure 6. Changes in running speed, HR, and V̇O2 across different sections in three pacing patterns.

Additionally, when analysing the runners' PBLa, RPE, and race times, Table 5 shows that the F-S pacing pattern had the lowest PBLa (15.0 ± 2.56 mmol/L), while the S-F pacing pattern had the highest (15.9 ± 1.86 mmol/L), with the Even pacing pattern in between (15.2 ± 2.01 mmol/L). There were no significant differences in PBLa values among the three patterns. For RPE, the F-S pacing pattern had the highest average, though again, there were no significant differences between the three patterns. Four out of six participants found the F-S pacing pattern the most uncomfortable, while two found the Even pacing pattern uncomfortable, suggesting that the F-S pacing pattern has a stronger psychological impact. The average RPE scores were around 16 for all pacing strategies. The average race times were 130.00 ± 1.96 s for F-S, 130.71 ± 1.93 s for Even, and 129.68 ± 1.49 s for S-F, with no significant differences in times. Interestingly, although the runners completed the same distance in almost the same time across the three pacing strategies, their metabolic responses and psychological perceptions differed slightly, despite no significant differences between the pace patterns.

Table 6. The peak blood lactate, RPE and race time after different paces.

No.	PBLa(mmol/L)			RPE			Race time(s)		
	F-S	Even	S-F	F-S	Even	S-F	F-S	Even	S-F
1	15.5	17.8	18.5	14	17	17	127.79	129.50	129.01
2	15.4	15.7	16.5	18	17	17	131.87	130.53	130.11
3	12.8	12.9	12.5	17	17	15	132.30	134.08	131.72
4	11.3	12.9	15.1	15	17	17	128.19	128.66	127.71
5	15.5	14.2	15.8	17	15	16	128.16	129.10	128.23
6	19.5	17.6	17.1	17	14	15	131.66	132.37	131.30
Mean	15.0	15.2	15.9	16.3	16.2	16.2	130.00	130.71	129.68
SD	2.56	2.01	1.86	1.37	1.21	0.90	1.96	1.93	1.49

Note. No significant difference in all groups.

DISCUSSION

Traditionally, analysing middle-distance running competitions involves manually reviewing videos to calculate speeds over each 100 m segment (Matsuo et al., 1992; Enomoto et al., 2005,2006; Kadono et al.2008; Yang & Enomoto, 2022a,b). However, this process is time-consuming and doesn't offer a complete performance analysis. While athletes can wear sensors to track their movements more accurately, this adds extra strain and can affect their performance (Ghasemzade & Jafari, 2010; Sheng et al., 2020). Additionally, lab-based measurements are limited as fitness equipment cannot fully replicate outdoor conditions or natural movement. Video-based detection and tracking offer a faster and more precise way to analyse races. With

the advancement of artificial intelligence, we can now perform this complex task using deep learning. Based on object detection, recognition, and tracking, we have developed a new method for video analysis and validated the feasibility of this method (Yang et al.,2023).In this study, we use a target detection algorithm to measure athletes' instantaneous speeds (Figure 5) and calculate their actual running distance (Table 3), introducing a more efficient method for performance analysis in middle-distance running competitions.

Figure 7 illustrates the interval speed (50m) from object tracking and manual video analysis for different runners in various pacing patterns. The black lines represent the interval speed from object tracking, while the grey lines indicate the interval speed from manual video analysis. A comparison of the speeds from object tracking and manual video analysis for all runners shows no significant difference between the two methods across different pacing patterns. Our previous research (Yang et al., 2023) also found no significant difference between the speeds from object tracking and manual video analysis when tracking a 1500 m race. Thus, object tracking proves to be effective in analysing speed in middle-distance running, and it can serve as a new method for performance analysis in such races. In addition, a larger total speed variation indicates greater speed fluctuation. Among the different pacing patterns, the Even pacing pattern showed a more stable running speed. However, there was no significant difference between the three pacing patterns (Table 4). Maintaining a stable speed may help reduce energy loss caused by excessive speed changes.

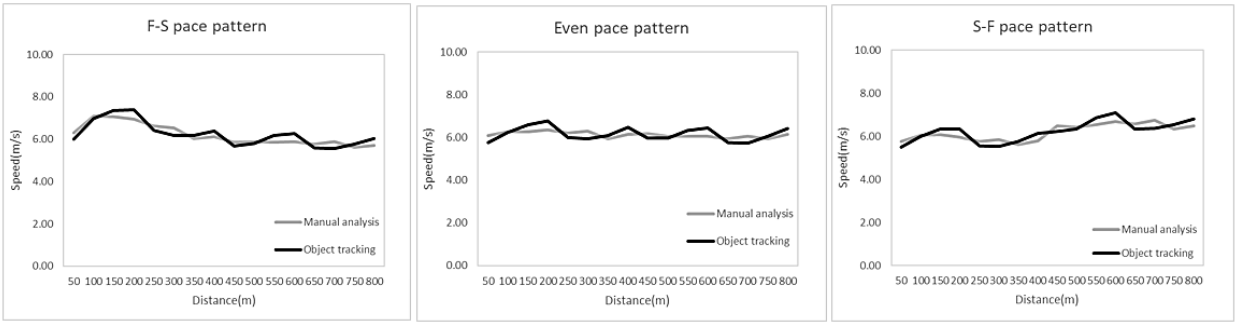

Figure 7. Average interval speed from object tracking and manual video analysis for runners with different pacing patterns.

Jones & Whipp (2002) noted that competition strategies and techniques can lead to runners covering different distances during a race. In their study on 800 m and 5000 m events, they found that athletes ran varying actual distances, which impacted performance. For example, in the Olympic men's 800 m final, Germany's Schumann won with a time of 1:45.08, running 802 m by staying close to the kerb, while Denmark's Kipketer, who finished second in 1:45.14, ran 813 m due to using lanes 2 and 3. Tracking athletes to measure their actual distance and pace is crucial for performance improvement. While formulas can estimate running distances, advancements in AI now allow us to track athletes using object tracking technology, providing more precise data on the distances covered. In our previous research, we tracked 1500 m runners during a race (Yang et al., 2023). The study also showed that when a runner completes an 800 m run alone, the actual distance covered remains nearly the same, regardless of different pacing strategies, with no significant differences observed between the three paces (Table 3). However, in real competitions, runners may cover greater distances due to overtaking and shifting into outer lanes. Consequently, overtaking or running in outer lanes can increase the total distance, highlighting the impact of race tactics on middle-distance performance. Running techniques and tactical decisions play a key role in influencing middle-distance running performance.

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Ariyoshi et al. (1979) were among the first to analyse three pacing patterns during a 1400 m treadmill run: Fast-Slow (F-S), Slow-Fast (S-F), and Even pacing. Their study emphasized the significance of the F-S pacing pattern in middle-distance running. However, as their experiments were conducted on a treadmill, their results may not fully reflect track performance, a limitation supported by subsequent studies on oxygen uptake in running (Spencer et al., 1996; Draper & Wood, 2005; Hanon et al., 2002; Thomas et al., 2005). To address this, our study conducted pace interventions on an actual track to simulate realistic conditions. Figure 8 illustrates the oxygen uptake patterns for runners under different pacing strategies. The F-S pacing pattern showed the smallest oxygen uptake area, followed by the Even pacing pattern, and then the S-F pacing pattern. While differences in oxygen uptake values among patterns were not statistically significant, the F-S pacing pattern demonstrated higher efficiency by minimizing energy cost. Effective pacing should optimize oxygen uptake without leading to excessive anaerobic metabolism. Hanon et al. (2007) noted that an overly fast start could be detrimental and recommended an initial speed below 115% of v$\dot{V}O_{2max}$ for no longer than 25–30 s. They proposed a pacing strategy that combines a fast but controlled start, energy conservation during the middle phase, and acceleration in the final 300 m. Similarly, Jones et al. (2008) modelled pacing strategies and found Fast Start (FS) to be the most effective in reducing oxygen deficits, although this conclusion was based on theoretical research. Our findings further validated the effectiveness of the F-S pacing pattern in real-world conditions but emphasized tailoring pacing to individual athletes' characteristics. In terms of $\dot{V}O_2$ dynamics, as shown in Figure 8, the F-S pacing pattern exhibits a slow start in oxygen uptake and a relatively low overall oxygen uptake during the race.

Additionally, Table 6 shows that the post-race PBLa, RPE, and race time values indicate that the F-S pacing pattern has the lowest PBLa (15.0 ± 2.56 mmol/L), while the S-F pacing pattern shows the highest PBLa (15.9 ± 1.86 mmol/L). The Even pacing pattern falls in between (15.2 ± 2.01 mmol/L). However, there were no significant differences in PBLa values among the three pacing patterns. From these observations, it can be inferred that in the F-S pacing pattern, runners accelerate rapidly at the beginning of the race, requiring a high energy output over a short period. During this phase, aerobic energy supply is delayed, and energy is primarily derived from anaerobic sources such as the ATP-PC system and glycolysis. The lower oxygen uptake at the start likely reflects the inability of the aerobic system to immediately provide sufficient oxygen, suggesting that anaerobic metabolism plays a significant role during this period. Furthermore, while the low lactate concentration might initially appear to indicate a limited contribution of anaerobic metabolism, it is possible that the F-S pacing pattern's strategy—reaching top speed quickly and then reducing pace—helps suppress overall energy expenditure. This efficiency may prevent excessive activation of glycolysis and the resulting accumulation of lactate.

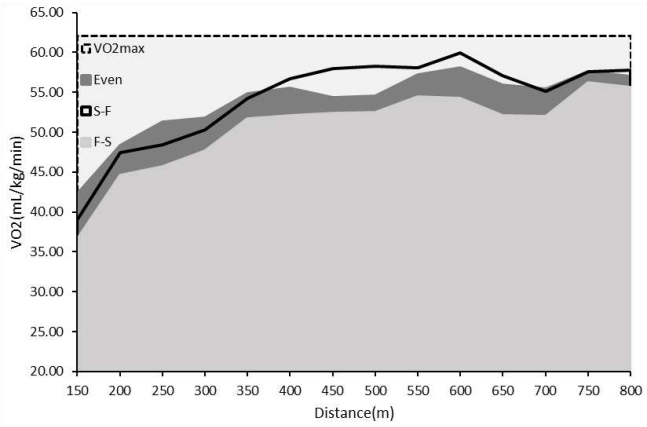

Figure 8. Dynamic changes in oxygen uptake across 50 m sections for three pacing patterns.

CONCLUSIONS

The objective of this study is to advance the understanding of how kinematic and physiological factors influence middle-distance running performance, with the goal of providing practical guidance for optimizing training strategies and improving athletic outcomes. This study investigated the physiological and kinematic effects of different pacing strategies in middle distance runners through experimental interventions on the track. The key findings are as follows:

Object tracking and kinematic analysis

The runners' speed changes and movement trajectories were tracked, showing that the Even pacing pattern had the lowest average total speed variation. The calculated distances for the three 800 m pacing patterns were: F-S (807.30 ± 0.88 m), Even (806.52 ± 0.66 m), and S-F (806.37 ± 1.63 m), with no statistically significant differences among them. The Even pacing pattern required the least work, followed by the F-S pacing pattern, while the S-F pacing pattern required the most, though these differences were not statistically significant.

Pacing and physiological metrics analysis

The F-S pacing pattern demonstrated lower oxygen uptake compared to the Even and S-F pacing patterns, indicating its efficiency in minimizing energy costs. Additionally, heart rate (HR) and oxygen uptake ($\dot{V}O_2$) stabilized more rapidly under the Even pacing pattern, while the F-S pattern resulted in the lowest post-race blood lactate concentration (15.0 ± 2.56 mmol/L), despite no statistically significant differences across strategies. The F-S pacing pattern showed lower oxygen uptake, underscoring its efficiency in minimizing energy costs. While the Even pacing pattern demonstrated more consistent speed control, all strategies exhibited significant energy expenditure during the initial phase due to rapid kinetic energy increases. The Even pacing strategy appears more suitable for maintaining consistent performance, while the F-S pacing pattern is advantageous for optimizing energy efficiency and oxygen utilization in competitive contexts.

This study bridges theoretical research and practical application, emphasizing the importance of personalized pacing strategies based on an athlete's physiological and kinematic profile. Future research should explore individual variations in response to pacing strategies, focusing on optimizing performance through tailored interventions. This work contributes to advancing middle-distance running analysis and lays a foundation for innovative approaches in training and competition.

AUTHOR CONTRIBUTIONS

Study concept and design, drafting of the article, and critical revision: Yongchang Yang and Yasushi Enomoto. Experimental assistance and data collection: Haruka Sugawara. Computer programming: Xinwei Lee. Data collection, interpretation and analysis, final approval of the version to be published: Yongchang Yang.

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ORIGINAL ARTICLE

Promoting inclusion and cognitive development through a basketball teaching laboratory

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ABSTRACT

This experimental study investigated the benefits of a basketball-based educational workshop to improve selective attention and the ability to inhibit automatic responses in 70 children from a first-year secondary school. The intervention had a significant impact on social inclusion and behavioural self-regulation, particularly for students with difficulties in these areas. By integrating physical and cognitive activities, the lab promoted cooperation and strengthened peer relationships, making the school a more inclusive environment. Changes in cognitive abilities were assessed using the Stroop test, The Index for Inclusion measured pre- and post-intervention levels of social inclusion. Statistical analyses using SPSS (version 27) showed significant changes in participants' performance, demonstrating the effectiveness of structured physical activity in improving executive function and cognitive development. The results highlight the importance of practical and playful educational strategies, such as sports workshops, to promote cognitive growth and create a more welcoming and cooperative school environment. This study adds to the literature demonstrating the value of interventions that combine physical and social activities to improve both learning and inclusion.

Keywords: Physical education, Executive functions, Motor-cognitive integration, Social engagement, Educational intervention.

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INTRODUCTION

Selective attention and the ability to inhibit automatic responses are fundamental processes of executive functions, which are closely linked to behaviour regulation, academic success and social development (Diamond, 2013). Executive functions include skills such as inhibitory control, working memory and cognitive flexibility, all of which are necessary to deal with complex situations and to change strategies according to context (Miyake et al., 2000). Numerous studies have shown that physical activity not only contributes to physical well-being, but also plays a crucial role in cognitive development, particularly with regard to executive functions in children and adolescents (Tomporowski et al., 2015). Activities that require motor coordination and quick decision-making, such as basketball, can directly stimulate these skills (Pesce et al., 2019). In addition, interventions that include playful components have been shown to be particularly effective in engaging children with SEN (Egger et al., 2020; Schmidt et al., 2021). Inclusion was promoted through the design of the activity, which ensured that all participants, regardless of their motor or cognitive abilities, could actively participate. The playful and collaborative approach of basketball provided an opportunity for socialisation and engagement, where the boys saw themselves as part of a group rather than as separate individuals with specific difficulties. This approach is supported by research highlighting how group physical activity can promote participation and reduce social exclusion behaviours in school settings (Pesce, Croce, & Benvenuti, 2019; Westfall, Dunsiger, & Bender, 2022). The present study aims to evaluate the impact of a basketball-based educational workshop on selective attention, inhibitory capacity, and level of educational inclusion in first-year secondary school students. To achieve this, the Stroop test was used to measure cognitive abilities and the Index for Inclusion was used to analyse changes in levels of social inclusion before and after the intervention.

MATERIALS AND METHODS

This study adopted a mixed research design using both quantitative and qualitative approaches to assess the effectiveness of a basketball-based teaching laboratory. The quantitative component was represented by the use of the Stroop test and the Index for Inclusion to measure inhibitory control, selective attention and social inclusion. The qualitative component of the study was structured through semi-structured interviews conducted with teachers and students at the end of the teaching workshop. This approach was chosen to explore participants' perceptions of the observed changes in behaviour, group dynamics and social inclusion. The interviews were designed following the methodological guidelines of Braun and Clarke (2006), using a grid of open-ended questions divided into three main thematic areas: (1) perceptions of the laboratory, (2) changes in social relationships and participation, and (3) learning of cognitive and behavioural strategies.

The interviews were conducted in a private setting and lasted on average 20-30 minutes. Questions to teachers focused on observing changes in group dynamics and pedagogical strategies that occurred during the activities. Pupils were asked questions to explore their sense of belonging to a group, their confidence in their peers and their ability to deal with complex situations during the laboratory. The main aim of these interviews was to understand how the intervention had affected both interpersonal relationships and cognitive skills.

The use of semi-structured interviews is based on the effectiveness of these tools in collecting rich and meaningful qualitative data, as suggested by Kvale and Brinkmann (2009). This approach allows the nuances of personal experience to be captured, providing a more complete perspective than quantitative data alone (Maxwell, 2012). In addition, the combination of quantitative and qualitative approaches addresses the need for triangulation of data, increasing the overall validity of the study (Creswell & Plano Clark, 2017).

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Participants

The sample consists of 70 students (mean age = 12.4 years, SD = 0.6; 36 males, 34 females) attending an urban primary school. Participants were selected through a school notice and participation was voluntary. Inclusion of all students, regardless of motor or cognitive ability, was ensured.

Measures

Stroop test: The Stroop test (Stroop, 1935) was used to measure inhibitory control and selective attention, two dimensions of executive function. The test consists of three conditions: (a) reading words indicating colours written in black, (b) naming the colours of printed squares, and (c) interference, where participants have to name the colour of ink used to write words of incongruent colours (e.g. "*red*" written in blue). Measures included mean response time and number of errors for each condition. In particular, the interference condition was considered to be the main indicator of inhibitory control. The test has good psychometric properties, with high levels of reliability and validity (Golden, 1978).

Index for Inclusion: To measure the level of social inclusion, the Index for Inclusion was used, which assesses school participation and peer interaction by assigning scores on a five-point scale.

Procedure

The didactic workshop was structured according to educational theories that support the importance of integrating motor and cognitive activities for the development of executive functions (Best, 2010). The sessions took place during school hours over a period of four weeks, with two weekly sessions of 90 minutes each. The proposed activities were modelled on the principles of cognitive training and integrative motor education as described by Diamond (2013) and Pellegrini (2009).

Session 1: Focus on selective attention

- Warm-up (20 minutes): motor exercises that stimulate selective attention, such as dribbling with directional changes in response to visual or auditory cues, were used. The approach is based on studies by Bissonette et al. (2013), which suggest that integrating motor and cognitive tasks improves concentration and attention regulation.
- Main activity (50 minutes): the main activity consisted of structured games that required selective attention. For example, participants had to complete at least three passes before they could draw. This exercise was inspired by research such as that of Hoare et al. (2003), which shows how the practice of cognitive rules in sports games can improve the ability to focus on multiple simultaneous stimuli.
- Cool Down (20 minutes): stretching exercises and guided reflection to improve concentration. The post-activity reflection was suggested by Scheredewahn et al. (2015), who highlight the importance of debriefing to consolidate changes in cognitive and behavioural functioning.

Session 2: Improving inhibitory control

- Warm-up (20 minutes): during the warm-up, exercises involving responses to conflicting stimuli were suggested, such as changing direction in response to opposite commands. This type of motor activity was suggested by Diamond (2013) as useful for improving inhibitory control, as it requires participants to resist automatic responses and respond only to relevant stimuli.
- Main activity (50 minutes): mini-games in which impulsive actions, such as shooting instantly without assessing the situation, were penalised. The adoption of rules that encourage reflection before action is based on the work of Best (2010), which shows how self-control and reflection in motor activities can improve executive functions.

- Cool Down (20 minutes): discussion and feedback on behaviour during the game, with a focus on self-regulation. The importance of reflective feedback is supported by studies such as that of Timmons et al. (2016), which suggest that post-activity discussions help to consolidate self-regulation and the integration of acquired cognitive skills.

Statistical analysis

Quantitative analyses were performed using SPSS software (version 27). Paired sample t-tests were used to compare pre- and post-operative performance on the Stroop test. Cohen's d was also calculated to determine the magnitude of the effect observed. The Index for Inclusion data were analysed using paired samples t-tests to compare mean pre- and post-intervention scores. A significance level of $p < .05$ was used.

Qualitative analysis was conducted using thematic analysis (Braun & Clarke, 2006) applied to data collected through semi-structured interviews. The interviews focused on three main thematic areas: (1) perceptions of the laboratory, (2) changes in social relationships and participation, and (3) learning of cognitive and behavioural strategies.

RESULTS

Quantitative results

Stroop test: the results showed a significant improvement in average response time and number of errors in the interference condition. Before surgery, the average response time was 35.2 4.5 seconds with an average of 5.3 1.2 errors. After surgery, the mean response time decreased to 28.7 3.8 seconds with a mean of 2.1 0.9 errors ($t(69) = 8.62$, $p < .001$, $d = 0.94$). These results indicate a significant improvement in inhibitory control and selective attention.

Social Inclusion Index: average social inclusion scores increased from 3.8 0.6 (pre-intervention) to 4.6 0.5 (post-intervention) on a 5-point scale ($t(69) = 7.54$, $p < .001$, $d = 1.33$). Teachers reported increased participation in group activities and reduced social exclusion behaviour.

Qualitative results

The qualitative analysis made it possible to capture deeper aspects related to the observed change in the students, thanks to the interviews conducted with teachers and participants. One teacher pointed out: "*I have noticed a significant change in the way students relate to each other. Children who were previously isolated started to participate actively, offering solutions during activities and interacting with their peers in a constructive way*". This comment reflects an improvement in self-esteem and a sense of belonging to a group.

The students also had their say. One of them said: "*During the games I felt that I could trust my team-mates and they trusted me. I had never felt like that before*". This testimony highlights how the workshop fostered a climate of mutual trust and cooperation, which helped to build positive relationships.

Another pupil, who initially found it difficult to follow the rules, said: "*At first it was hard not to shoot immediately, but then I realised that it was better to pass the ball and wait for the right moment. I felt calmer and could think more about what I was doing*". This change reflects an improvement in inhibitory control and planning ability.

Teachers also observed a positive impact on group dynamics. One teacher commented: "*The activity created an environment where every pupil felt valued. Even the normally shy ones started talking and working with*

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others". This observation suggests that the lab not only improved cognitive skills but also helped to create an inclusive and welcoming environment.

DISCUSSION

The results of this study suggest that the integration of structured physical activity, such as basketball, into the school curriculum can be an effective tool for developing executive function and promoting social inclusion. The improvements observed in participants' cognitive performance on the Stroop test, particularly in the interference condition, are consistent with numerous studies showing how physical activity can positively influence inhibitory control and selective attention (Best, 2010; Pesce et al., 2019). This supports the hypothesis that integrated physical and cognitive training is not only beneficial for physical well-being but also has a profound impact on cognitive development and behavioural self-regulation.

An important aspect of this study is the playful and cooperative approach used in the basketball sessions. This method was found to be particularly effective in engaging students and encouraging active participation, including those with motor, cognitive or social difficulties. The studies by Egger et al. (2020) and Schmidt et al. (2021) have shown that playful and collaborative environments can be a crucial motivational lever to promote inclusion and participation of students with special educational needs. These interventions also contribute to a greater sense of belonging and mutual trust among participants, as evidenced by the qualitative comments collected in this study.

Another interesting element is the multidimensional approach used, which combines motor exercises with cognitive components and guided reflection. This type of intervention, in addition to improving cognitive test performance, seems to have a positive impact on the social behaviour of the students, as evidenced by the increase in scores on the Index for Inclusion. The literature supports the idea that educational interventions that include both physical exercise and cognitive empowerment can significantly improve social inclusion (Tomporowski et al., 2015; Westfall, Dunsiger, & Bender, 2022). In particular, students who were typically on the margins of school activities were encouraged to participate through a structured environment that promoted collaboration rather than competition.

The qualitative findings of the study provide an additional level of understanding, highlighting that the changes observed in participants were not limited to cognitive skills, but also included improvements in relational dynamics and emotional well-being. For example, students' statements about feeling part of a group and teachers' statements about being part of a group that emphasised the active participation of previously isolated students reinforce the concept that group physical activity can foster empathy and positive relationship building (Pesce et al., 2019; Diamond, 2013). These improvements suggest that the workshop promoted not only individual skills, but also social skills that are essential for academic and personal success.

A distinctive feature of this intervention is the integration of exercises designed to stimulate inhibitory control and selective attention in a dynamic, cooperative environment. This approach differs from traditional interventions, which often address executive functions in more static contexts, such as purely cognitive or individual activities. Previous studies, such as those by Diamond (2013) and Best (2010), have highlighted the importance of simultaneously engaging the mind and body to achieve more significant and lasting benefits in cognitive function.

Another point of discussion is the possibility of implementing similar programmes on a large scale. Although the results of this study are promising, large-scale implementation of interventions based on basketball or

other structured sports activities would require appropriate teacher training and specific resources. However, studies such as Schmidt et al. (2021) suggest that investment in such programmes could lead to significant long-term benefits, both for student well-being and for creating an inclusive school environment.

Finally, it is important to recognise some of the limitations of the study. Although the results were statistically significant, the analysis was carried out on a relatively small and limited sample. Future studies could investigate the effectiveness of similar interventions in a larger and more diverse population, including a variety of socio-economic and cultural contexts. It would also be useful to examine the long-term effects of the intervention to determine whether the observed benefits are sustained over time.

In conclusion, this study adds to the body of scientific evidence on the effectiveness of educational interventions based on physical and recreational activities for improving executive functioning and social inclusion. The results suggest that such interventions can be a powerful and versatile educational strategy, able to meet the needs of students with different abilities and backgrounds, while promoting a more welcoming and supportive school environment.

CONCLUSION

The results of the study show how a basketball-based teaching workshop can be an effective educational strategy for improving executive function and promoting social inclusion. This approach was found to be particularly useful for students with self-regulation difficulties, creating a more welcoming and cooperative school environment. Activities that integrate physical and cognitive components, such as those proposed in this study, can be powerful pedagogical tools that can strengthen students' cognitive and relational skills.

A large body of previous research supports the idea that exercise can have a positive impact on executive function. For example, Diamond (2013) highlights how physical activity, including sport, can stimulate the brain area involved in the control of higher cognitive functions, such as attention and working memory. In addition, structured physical activity, such as team-based activities, has been linked to improved emotional and social regulation, as demonstrated by Randler et al. (2014), who found improvements in participants' cooperative skills and relational dynamics. The success of the intervention suggests that the implementation of similar programmes on a large scale could be a significant step towards more inclusive and resilient education. In particular, this type of approach could be used to target groups of students with difficulties in self-regulation and behaviour management. Incorporating structured and playful activities into the classroom not only improves cognitive performance but also promotes a more cooperative and supportive school environment. These approaches are in line with the principles of inclusive education as proposed by Ainscow (2005), who emphasises that a positive and supportive school environment promotes the success of all pupils, regardless of their individual difficulties. Future research could further explore the effectiveness of this approach with different age groups and in different school settings, thus contributing to the validation and expansion of innovative educational strategies. In particular, future studies could examine the impact of these programmes in different cultural and social contexts to better understand how variables such as culture and school resources can influence the effectiveness of physical activity-based interventions.

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The writing of this paper was a joint effort by all authors.

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ORIGINAL ARTICLE

Sitting volleyball and inclusion: An emotional and relational analysis in a lower secondary school

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ABSTRACT

This study explores the effectiveness of sitting volleyball as a pedagogical tool for promoting school inclusion and emotional well-being among students with and without physical disabilities in a lower secondary school. Involving 40 students, divided into an experimental and a control group (both with an equal representation of students with motor disabilities), the research adopts a mixed methodological approach, combining quantitative tools (EQ-i:YV and SADI scale) and qualitative tools (semi-structured interviews). The educational intervention consisted of a 12-week programme based on sitting volleyball, designed with cooperative and inclusive goals. The results show a significant increase in emotional self-awareness, sense of belonging and quality of interpersonal relationships in the experimental group compared to the control group, confirming the transformative impact of adapted sport in school settings. The study highlights the need to rethink school physical education practices in an inclusive way and proposes sitting volleyball as a virtuous model of relational and participatory education.

Keywords: Physical education, Sitting volleyball, Inclusion, Physical disability, EQ-i YV, SADI, Secondary school, Classroom climate, Emotionality.

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INTRODUCTION

Adapted physical activity is now one of the most effective tools for promoting school inclusion and supporting the psychological well-being of students with disabilities. One of the most inclusive school sports is sitting volleyball. It is a variation of traditional volleyball played by athletes sitting on the ground, with a lower net and a smaller playing field. This discipline, which originated in the Paralympic movement, allows people with and without disabilities to actively participate and promotes a cooperative and accessible approach that values diversity as a resource (World ParaVolley, 2021). Due to its structure, sitting volleyball eliminates many of the physical barriers typical of traditional motor activities, creating an environment where individual ability is not the only criterion for participation, but rather collaboration and mutual respect (Bertagna, 2012). In a school context, sitting volleyball is a powerful educational tool that can combine physical activity, relationships and personal development. It allows students with disabilities to feel an active part of the group, improving their self-perception and increasing their self-efficacy, while promoting the development of empathy, solidarity and a sense of responsibility in their peers without disabilities (Block & Obrusnikova, 2007). These dynamics contribute to building a more inclusive and harmonious classroom environment, where the group perceives itself as a cohesive community.

According to UNESCO (2017), truly inclusive education is education in which all students, regardless of their personal or social circumstances, participate fully and equitably in school life. In this perspective, psychological well-being plays a central role, understood as a balance between the emotional, relational and motivational dimensions of the student. Several studies have shown that participation in adapted sports, especially cooperative activities such as sitting volleyball, has a positive impact on various aspects of psychological well-being: it increases self-esteem, reduces social anxiety, promotes positive emotions and improves interpersonal relationships (Sherrill, 2004; Groff et al., 2009; Valentini & Rudisill, 2004). Play, understood as a relational and symbolic space, allows individuals to explore and consolidate their emotions in a protected and motivating environment, especially when it is oriented towards inclusion and collaboration (Goodwin, 2001). Sitting volleyball, with its participatory and non-selective structure, thus becomes a catalyst for well-being and belonging for all students, helping to reduce the distance between those who are 'different' and those who are considered 'able-bodied'. In light of this evidence, the present study aims to analyse the impact of sitting volleyball on the emotional well-being and perceptions of inclusion of students with physical disabilities, comparing the results with those of a control group. The aim is to understand whether and how the structured practice of this discipline can promote fair and generative educational processes, strengthen class cohesion and promote a more humane, motivating and sustainable school environment.

Aim of the research

This study aims at analysing its impact on emotional well-being and perceptions of inclusion of pupils with physical disabilities in secondary education. The main objective of this research is to analyse the impact of sitting volleyball on emotional well-being and perceptions of inclusion in school among students with physical disabilities attending a lower secondary school. In particular, the study aims to test whether an adapted physical activity intervention, based on principles of cooperation and active participation, can positively influence dimensions such as emotional self-perception, the quality of peer relationships and the sense of belonging to the class group. A comparison with a control group engaged in traditional physical activities will also allow us to assess the extent to which sitting volleyball can be a more effective alternative for promoting truly inclusive environments and supporting the socio-emotional development of students with and without disabilities.

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METHODS

Sample selection

The study involved a total of 40 students enrolled in a lower secondary school, divided equally into two groups:

- Sample group: 20 students, including 5 with lower limb disabilities, participating in a structured seated volleyball programme;
- Control group: 20 students, including 5 with lower limb disabilities, participated in traditional physical activities during physical education classes.

The inclusion criteria were defined in a similar way to those used in the scientific literature on physical activity in schools and adapted accordingly. In particular, following the study by Tafuri et al. (2023) on the effects of Pilates on adolescent athletes, strict criteria were also adopted for this project:

- Age group between 11 and 13 years, corresponding to the first and second years of lower secondary school;
- Presence of physical disability in the lower limbs (e.g. paraplegia, paresis, amputations or other motor limitations not associated with cognitive disability), not associated with cognitive disability;
- Ability to understand and follow simple instructions,
- Absence of clinical conditions that could compromise participation or alter the results.

Participation in the study required the completion of an informed consent form by parents or legal guardians, in accordance with the Declaration of Helsinki and its subsequent revisions, with guarantees of data confidentiality and the right to withdraw at any time. In the preliminary phase, an information session was also organised for families and teachers to explain the aims, methods and expected benefits of the study. Participants were recruited in collaboration with the school and the PE teaching team, ensuring a heterogeneous sample in terms of gender, academic performance and socio-cultural background, and an equal distribution of variables between the two groups. This procedure ensured the comparability and validity of the data, allowing for an accurate analysis of the effectiveness of sitting volleyball compared to traditional physical activities in terms of inclusion and emotional well-being.

Research tools

The study adopted a mixed methods approach, combining quantitative and qualitative tools with the aim of gaining an integrated and in-depth understanding of the dimensions of emotional well-being and perceived school inclusion, in line with Creswell and Plano Clark's (2017) recommendations on the effectiveness of integrated research designs in education.

Among the quantitative tools, the EQ-i:YV (Emotional Quotient Inventory: Youth Version) questionnaire was used, which is a validated scale for measuring emotional intelligence in individuals between the ages of 8 and 18 (Bar-On & Parker, 2000). This tool allows the detection of dimensions that are fundamental to the well-being of adolescents, such as self-awareness, stress management, interpersonal skills and adaptability, all of which are crucial components in inclusive contexts (Zins et al., 2004). In particular, the present study focused on self-awareness, understood as the ability of individuals to recognise and understand their own emotions, thoughts and behaviours. This ability is a fundamental prerequisite for the development of effective interpersonal relationships and the strengthening of personal identity within the class group. The questionnaire was administered before and after the intervention to all students in both groups, with the aim of detecting any changes in self-perceived emotional intelligence following participation in the adapted physical activity programme.

Alongside this tool, the Scale for the Analysis of Inclusion (SADI) was used to explore students' subjective perceptions of inclusive processes in the school context. The scale takes into account aspects such as sense of belonging, peer relationships and level of active participation in educational activities, which are considered key indicators of an inclusive school environment (Booth & Ainscow, 2011).

On the qualitative side, data were collected through semi-structured interviews with students with and without disabilities and physical education teachers. Interviews with students focused on experiences and feelings related to sport, the quality of peer relationships and perceptions of being an integral part of the group. The interviews with teachers explored the observed impact of sitting volleyball on class cohesion, the inclusion of students with disabilities and the overall effectiveness of the inclusive intervention. In this sense, the narrative approach allowed for a deeper understanding of the participants' points of view, highlighting the subjective and experiential dimensions of inclusion (Goodley, 2013; Denzin & Lincoln, 2018). Qualitative data analysis was conducted using NVivo software, which allowed the content of the interviews to be coded, categorised and analysed thematically. The use of NVivo facilitated the emergence of interpretative patterns and shared meanings, contributing to the triangulation of data and cross-validation of findings (Bazeley & Jackson, 2013).

This enabled a deeper understanding of the inclusive processes and emotional dynamics triggered by sitting volleyball in a school setting. In summary, the combination of standardised quantitative tools and qualitative interviews allowed not only the measurable effects of the intervention to be explored, but also its perceived impact, providing a comprehensive and detailed overview of the educational and relational value of adapted sport in schools.

EDUCATIONAL PROGRAMME

The educational programme was developed over a 12-week period, with two weekly sessions of one hour each taking place during regular physical education classes. The intervention was based on a deliberate and differentiated curriculum for the sample and control groups to assess the impact of adapted sport compared to traditional physical activity. The sample group followed a structured sitting volleyball programme led by a physical education teacher with specific training in inclusive sport, supported by a specialised sports educator. The programme was divided into three progressive teaching phases, each with specific objectives and targeted activities:

Initial phase (week1-3)

Aims: To learn the basic rules of Sitting Volleyball, to become familiar with the sitting position and the basic movements.

Activities: Warmups on the floor, individual rolling and movement exercises on the floor, simple passing (dribbling and passing) between seated teammates, mini drills.

Tools: Lightweight foam balls, coloured ribbons to mark out the court, non-slip mats to make sitting easier and protect the joints.

This introductory phase focused on overcoming the initial physical and psychological barriers associated with the new way of moving and sitting. As Rizzuto (2012) points out, a gradual approach is essential to promote a sense of perceived competence in individuals approaching adapted disciplines.

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Intermediate phase (week 4-8)
Aims: Development of group dynamics and cooperative play.

Activities: Paired exercises to improve passing accuracy, team games with common goals (e.g. keeping the ball in the air for a certain number of exchanges), role rotation (server, receiver, setter), symbolic games to develop empathy.

Tools: Regulation volleyball net (reduced height), soft volleyballs, cones for orientation exercises, visual aids to explain the rules.

In this central phase, the sense of belonging and identity of the class group was strengthened through cooperative learning practices, which, as demonstrated by Johnson and Johnson (2009), are a powerful tool for improving peer relationships and promoting inclusion. The adoption of variable roles and shared game objectives allowed students to enjoy equal and non-competitive experiences, developing cross-curricular skills such as effective communication, turn-taking and empathy (Zanobini & Usai, 2015).

Advanced phase (week 9-12)
Aims: Consolidating technical and emotional skills, reflecting on experiences, increasing self-efficacy.

Activities: Mini-tournaments with mixed teams, timed games, game simulations, closing circle time with feedback, narrative of emotions experienced.

Tools: Scoreboard, emotional self-assessment sheets, personal sports diary for written reflection, videos for self-observation of key moments.

The final phase aimed to integrate technical and motor skills with emotional and reflective skills, promoting metacognition and self-evaluation processes. Bandura (1997) highlights how perceived self-efficacy is enhanced through direct experience of success and the opportunity to reflect on one's progress.

The entire programme was guided by a strongly inclusive approach, where functional differences between students were not seen as barriers, but rather as valuable resources for mutual learning and group growth. In line with UNESCO guidelines (2017), which promote inclusive and participatory education, activities were designed to enhance the potential of each pupil by fostering a cooperative and supportive atmosphere. The adoption of cooperative learning based on heterogeneous groups and common goals encouraged shared responsibility and mutual support among peers (Johnson, D.W., & Johnson, R.T., 2009), making motor experience a privileged context for inclusion and socio-relational development. The teacher consistently used a teaching style based on emotional scaffolding, providing motivational support, constant encouragement and positive feedback, which also valued small successes and strengthened self-efficacy, particularly in pupils with disabilities. This approach was instrumental in creating a peaceful, motivating and safe environment where everyone could express themselves without fear of judgement. At certain points in the unit, structured circle time sessions were planned, during which pupils had the opportunity to talk about their experiences and share their feelings, difficulties and satisfactions related to sporting activities.

These moments of reflection strengthened group cohesion and fostered the development of empathy, emotional awareness and mutual listening skills, reducing discriminatory attitudes and promoting a culture of genuine inclusion. As Goleman (1995) points out, these socio-emotional skills are fundamental to individual well-being and to building meaningful relationships in the school context. Another key element of the

programme was the allocation of inclusive roles of responsibility: every student, regardless of their physical condition, was able to try their hand at active and meaningful tasks such as captain, timekeeper, observer, game organiser or group motivator. This promoted student leadership, strengthened their sense of belonging to the school community and encouraged autonomy and deliberate participation. This approach is consistent with the Universal Design for Learning perspective (CAST, 2018), which supports the need to provide multiple modes of engagement to ensure equal opportunities for success for all students.

The control group, on the other hand, participated in a traditional physical education programme in line with the ministerial guidelines for the age group (11-13 years). The focus was on developing conditional abilities (strength, endurance, speed) and coordination, with a predominantly performance-oriented approach and less emphasis on relational inclusion. The programme was divided into three thematic modules:

Module 1: General gymnastics, motor circuit training (week 1-4)
Activities: Warm-up, stretching, bodyweight exercises (abdominals, push-ups, squats), obstacle courses with jumps, slalom and relays.

Tools: hoops, obstacles, mats, gymnastic sticks, stopwatches.

In this initial phase, the focus was on the development of basic conditioned skills, particularly strength, joint mobility and general endurance. Bodyweight and functional exercises are an important resource for consolidating motor control and preventing injury in pre-adolescents, as highlighted by Bompa and Haff (2009).

Module 2: Sports Games (week 5-9)
Activities: Simplified football and basketball games, relay races, team games (poisoned ball, dodge ball), dribbling exercises and shooting at goal/basket.

Tools: Football and basketball balls, coloured bibs, cones, mobile goals and adjustable basketball nets.

This second phase promoted the introduction of basic sports skills and active participation in team dynamics. Sport is a preferred method of physical education as it combines technical learning, social development and respect for shared rules (Côté & Fraser-Thomas, 2007). However, in this module there was a greater emphasis on the competitive rather than the inclusive component, with activities organised mainly around performance and results, as is often the case in more traditional models of physical education (Bailey et al., 2009).

Module 3: Resistance and coordination activities (week10-12)
Activities: Time trials (400m), multi-stage endurance circuits, balance and reaction games, rope skipping.

Tools: stopwatches, cones, skipping ropes, ropes.

In the final module, the focus shifted to the development of aerobic endurance and general coordination skills. These skills are particularly important in the pre-adolescent age group as they contribute to the consolidation of the neuromuscular system and the development of an active lifestyle (Malina, Bouchard & Bar-Or, 2004).

Although the lessons were minimally adapted to allow students with motor disabilities to participate (e.g. elimination of the most complex obstacles, simplification of roles in team games), no explicit inclusive strategies or moments of reflection on emotional and relational experiences were integrated.

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RESULTS

Quantitative data analysis

The analysis of the quantitative data obtained from the pre- and post-intervention administration of the EQ-i:YV (Emotional Quotient Inventory: Youth Version) questionnaire and the SADI (Self-Determination and Inclusion Scale) revealed statistically significant differences between the sample group (exposed to the sitting volleyball programme) and the control group (involved in traditional physical activities). These tools were chosen for their scientific validity in assessing emotional intelligence and sense of inclusion in school among adolescents, respectively. The data were analysed using repeated measures analysis of variance (ANOVA), which makes it possible to detect changes within subjects over time and between different groups. This statistical approach, already used effectively by Tafuri et al. (2022) in their study Effects of Pilates training on the physical, physiological and psychological performance of young and adolescent volleyball players, proved particularly useful in highlighting the interaction between the variables time (pre/post) and group (experimental/control), increasing the sensitivity of the analysis to changes induced by the educational intervention. The results obtained showed a significant effect of time ($p < .01$) and, in particular, of the time x group interaction ($p < .01$) for the self-awareness variable measured by the EQ-i:YV. In particular, the sample group showed an average increase in post-intervention scores of 18.5%, compared to a more modest increase in the control group of only 5.3%. These data highlight the effectiveness of the proposed integrative programme in stimulating students' awareness of their emotions, thoughts and behaviours, a core skill for the development of empathy, self-regulation and the ability to build meaningful relationships.

The ANOVA analysis also showed a significant effect of treatment on the SADI scale, which assesses aspects related to school participation, self-determination and sense of belonging. The sample group showed an average improvement of 21.7%, with particularly marked progress in the sub-dimensions of sense of belonging and active participation, two key indicators of school involvement and psychosocial well-being. In contrast, the control group showed an overall increase limited to 6.9%, with virtually unchanged scores for the perception of the quality of peer relationships and only slight improvements in participation.

These results clearly show that adapted sports activities, when well-structured and supported by a solid pedagogical framework, can play a crucial role in promoting a more inclusive, collaborative and motivating school environment. In contrast, the more traditional programme followed by the control group, which focused on individual motor performance, had less impact on socio-relational and emotional aspects, confirming the need to rethink physical education in schools, moving beyond a technical performance approach to a more educational and inclusive vision of sport.

The results obtained, supported by rigorous statistical analysis, are in line with recent scientific literature on the impact of adapted sport on the personal and social development of adolescents. In particular, sitting volleyball, due to its cooperative nature and the removal of physical and symbolic barriers, is a powerful tool for integration, promoting the reduction of inequalities, the empowerment of students and the promotion of diversity.

Qualitative data analysis

The qualitative analysis, conducted through semi-structured interviews, provided an in-depth and detailed insight into the experiences of the students and teachers and revealed significant differences between the sample group involved in sitting volleyball and the control group involved in traditional physical activities. The data, processed using NVivo software, highlighted the emergence of interpretative patterns consistent with the themes of inclusion, self-efficacy, sense of belonging and quality of interpersonal relationships. In the

sample group, students - both with and without disabilities - described the sitting volleyball context as an emotionally safe space where everyone felt welcome and valued. The words of a student with a motor disability sum up this perception: "*For the first time I really felt part of the team. I didn't have to chase after the others, we were all sitting together, all equal*". This statement reflects the idea of fairness and equal access that is at the heart of inclusive processes. Another able-bodied pupil also highlighted a significant change in his perception of disability: 'Playing together made me realise that we are not so different. In fact, I have learnt a lot from those who have more difficulties than me'. This kind of reflection is clear evidence of the activation of empathic dynamics and the construction of deeper and more conscious interpersonal relationships.

On the teachers' side, the teacher in the sample group emphasised the transformative effect of the collaborative approach adopted: "*With sitting volleyball, I saw skills emerge that normally remain hidden: the shyest students spoke up, and students with disabilities became points of reference for others*". This observation highlights how the relational dimension and the inclusive protagonism had concrete effects on the classroom climate and on the students' self-perception.

In contrast, in the control group, the students' narratives focused mainly on motor performance and competition. The emotions expressed were often related to frustration with sporting results or difficulties in keeping up with the exercises. A student with a partial disability said "*Sometimes I felt like a burden. The others were running, I had to do things my way, but no one was waiting for me*". Similarly, one of his classmates said: "*I felt sorry for him, but during the races it was difficult to get him really involved*". These testimonies indicate a lack of strategies to encourage active participation and shared responsibility, which are key elements of truly inclusive learning.

The control group teacher also acknowledged some critical issues: 'We have tried to adapt the activities, but without really inclusive planning it is difficult to involve everyone at the same level. The group dynamic often remains competitive.

In contrast to the sample group, there were no moments of structured reflection or spaces for sharing emotional experiences, so interpersonal relationships remained at a more superficial level.

In conclusion, the qualitative findings confirm the effectiveness of Sitting Volleyball in promoting an educational environment that values diversity, facilitates empathy and strengthens a sense of belonging. The authentic and meaningful voices collected are concrete evidence of the transformative power of inclusive sport, which not only improves emotional skills, but also has a tangible impact on the quality of school life and peer relationships.

DISCUSSION

The results of the study clearly and comprehensively confirm the effectiveness of educational interventions based on adapted sport, in this case sitting volleyball, as a preferred tool for promoting school inclusion and emotional well-being among students. The combination of quantitative and qualitative data made it possible to capture both objective changes in terms of emotional intelligence and sense of belonging, as well as the subjective nuances of the experience, highlighting the transformative impact of inclusive physical activity. The significant increase in levels of self-awareness and active participation in the sample group suggests that a collaborative, empathetic and relationship-centred approach can have a profound impact on the construction of personal and social identities of students, particularly those with disabilities. As Sherrill and

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Hutzler (2006) state, adapted physical education not only promotes the development of motor and social skills, but also contributes to the creation of an inclusive climate in which each individual can feel valued. In line with Goodwin and Watkinson (2000), active participation in inclusive sporting contexts offers students with disabilities the opportunity to redefine themselves through successful experiences, thus helping to improve their self-esteem and their perception of their role in the group. The testimonies collected, rich in emotions and reflections, show that sitting volleyball was not only an alternative sporting context, but also a real space of mutual recognition, where everyone could try out active and meaningful roles, regardless of their physical condition. This approach, in line with the inclusive pedagogy proposed by Booth and Ainscow (2011), promotes the establishment of a cooperative dynamic in which diversity becomes a resource rather than a limitation. In stark contrast, the dynamics observed in the control group highlight the limitations of an educational approach focused on individual achievement, which tends to implicitly exclude those who do not meet standardised motor skill criteria. This confirms the critical issues identified by Morin (2000) and Sutherland (2004), who highlight how non-inclusive teaching practices can reinforce inequalities and undermine the sense of belonging of the most vulnerable pupils.

However, despite the encouraging results, some critical points should be noted. Firstly, the effectiveness of the intervention could be influenced by the intrinsic motivation of teachers and their training in inclusive education: not all PE teachers have specific skills in delivering adapted activities. As highlighted by Block and Obrusnikova (2007), the lack of specific training can be a significant barrier to the full implementation of inclusive practices. Furthermore, the long-term sustainability of such interventions requires the support of the whole school system, as well as adequate material resources and flexible teaching hours, which are often difficult to find within traditional school organisations. Finally, another limitation concerns the sample size and the relatively short duration of the intervention, which does not allow for an in-depth assessment of the long-term effects on the personal and social development of the pupils.

Future ideas could include:

- The systematic introduction of inclusive sport into school curricula through permanent, interdisciplinary modules;
- The promotion of specific training courses for teachers, in order to strengthen skills in adapted physical education;
- The adoption of broader assessment tools that are more sensitive to the socio-emotional dimensions of pupils;
- Testing similar practices in different school settings (e.g. primary schools, vocational centres) to test their effectiveness on a larger scale. In summary, these findings, in line with recent literature (Haegele & Sutherland, 2015; Lieberman & Houston-Wilson, 2018), suggest an urgent need for a pedagogical overhaul of physical education practices so that they become true laboratories of citizenship, relationships and personal growth, where diversity is no longer experienced as an obstacle, but as a value on which to build a truly inclusive school.

CONCLUSION

The survey conducted highlighted how the integration of sitting volleyball in schools represents a significant educational opportunity to promote inclusion, emotional well-being and peer relationships. Adapted sport, as an educational practice focused on fairness and active participation, is a valuable tool for promoting diversity and overcoming stereotypes and barriers (Benedetti, 2019). The mixed-methods approach adopted made it possible to clearly identify both the objective benefits in terms of self-awareness, self-esteem and self-

perception, and the subjective changes experienced by the students and teachers involved, confirming the importance of a holistic evaluation of the educational process (Creswell & Plano Clark, 2011).

The comparison between the sample group and the control group highlighted the effectiveness of a teaching approach based on cooperation, empathy and the value of differences, compared to traditional physical education, which still often focuses on performance and competition (Capranica & Guidotti, 2016). The methodology adopted activated inclusive relational dynamics, promoting a more cohesive, welcoming and motivating school climate, in line with the theories of cooperative learning (Johnson & Johnson, 2009) and inclusive education (Booth & Ainscow, 2008).

The data collected confirms that adapted sport, when included in a deliberate educational project and supported by reflective and inclusive practices, can become a powerful catalyst for personal and collective growth, contributing to the construction of a more equitable, participatory and humane school environment. As Galligani (2020) points out, sport in schools can be experienced as a space for cultural and social mediation, capable of generating a sense of belonging and active citizenship.

In the light of these results, we hope to see similar programmes implemented in lower secondary schools and, more generally, the adoption of educational models that recognise sport not only as an opportunity for physical exercise, but also as a vehicle for educational and social transformation. At a time when inclusion is an essential challenge for the education system, experiences such as the one described above demonstrate that it is possible to build school spaces where everyone, with their own characteristics and potential, can feel fully part of the community (Morin, 2001; Tramacere, 2020). It is only through teaching that is attentive to relationships, needs and differences that a school can truly be created that is capable of welcoming and valuing each pupil.

AUTHOR CONTRIBUTIONS

Introduction and conclusions: Tafuri, M. G. Methods: Scala, G. Educational programme: Di Palma, D. Results: Gravino, G. Discussion: Romano, G.

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ORIGINAL ARTICLE

Motor development in school-aged children: A comparison of structured and unstructured physical activity environments

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ABSTRACT

The present study aims to investigate the influence of structured physical activity (SPA) and unstructured physical activity (UPA) environments on the development of locomotor skills in primary school children. The sample consisted of 148 pupils (mean age = 8.7 ± 0.7 years; 77 girls and 71 boys) attending the third and fourth grades of a primary school located in a rural municipality in southern Italy. Motor skills were assessed by means of the locomotion subtest of the Test of Gross Motor Development – Third Edition (TGMD-3). The results show that 86.5 % of the participants (n = 128) engage in UPA during their leisure time. The mean scaled score for the entire sample was 8.23 points (± 2.68), with 64.2 % of the pupils falling within the "*Average*" level. Children who participate in SPA obtained significantly higher scores than their peers who do not practise structured activity: 8.64 (± 2.74) vs 7.73 (± 2.53) points; p = .038; Cohen's d = 0.34. Multifactorial analysis confirmed a positive main effect of SPA but did not reveal significant interactions between SPA and UPA. Although the data confirm the influence of structured activity on locomotion test outcomes, the non-significance of UPA may be attributable to the characteristics of the subtest items, as these tasks are widespread in sporting practice. The findings highlight the role of rural contexts in promoting unstructured physical activity among school-age children and the contribution of structured physical activity to the development of motor skills. Future research should consider enlarging the sample, including the object-control subtest of the TGMD-3, and further exploring the qualitative relationships between SPA, UPA, and motor development.

Keywords: Physical education, Fundamental movement skills, Locomotor competence, TGMD-3, Rural context, Open- and closed-skill sports, Free play.

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INTRODUCTION

Physical activity (PA) can be understood as a set of actions and performances shaped by cultural, emotional, ideational and relational factors: "*physical activity involves people moving, acting and performing within culturally specific spaces and contexts, and influenced by a unique array of interests, emotions, ideas, instructions and relationships*" (Piggin, 2020).

A large body of research highlights the crucial role of PA in youth development, documenting its beneficial effects on multiple dimensions of physical and mental health (Coppola et al., 2024a; Biddle & Asare, 2011; Janssen & LeBlanc, 2010) as well as on socio-emotional and cognitive outcomes (D'Anna et al., 2025; Coppola, D'Anna, et al., 2024; McNeill, Howard, Vella, Santos & Cliff, 2018; Ahn, Sera, Cummins & Flouri, 2018; Carson et al., 2017; Donnelly et al., 2016; Rasberry et al., 2011; Best, 2010). In childhood, PA decisively fosters the acquisition and consolidation of motor skills (Coppola et al., 2024b; D'Anna et al., 2022; Iivonen & Sääkslahti, 2014; Timmons et al., 2007).

A childhood marked by regular PA reduces the early onset of risk factors for chronic diseases in adulthood (Strong et al., 2005). Nevertheless, most children (both in high-income and in middle- and low-income countries) do not attain adequate PA levels (Bouchard et al., 2012). Globally, 81 % of young people do not meet international recommendations for daily movement, exposing their present and future health to significant risks (Guthold et al., 2020). Evidence indicates that sedentary behaviour and inactivity, rather than energy intake (which tends to remain stable), explain the decline in physical performance (Tomkinson et al., 2003). At the same time, the amount of time spent in front of television or digital screens is increasing (Twenge & Campbell, 2018; Ten Velde et al., 2021).

This dynamic, characterised by insufficient motor practice and a predominantly sedentary lifestyle, reduces the individual motor repertoire and weakens the protective effects of PA. Such a condition gradually favours childhood overweight and obesity (Mazur et al., 2018, cited in Colella & Vera, 2020). In addition, a sedentary lifestyle during development is associated with negative outcomes for cognitive and brain health, with repercussions for school performance and executive functions (Pontifex et al., 2011; Chaddock et al., 2011; Chaddock et al., 2010a, 2010b; Hillman et al., 2009; Hillman et al., 2008; Castelli et al., 2007).

Article 31 of the United Nations Convention on the Rights of the Child (1989, ratified in Italy by Law 176/1991) recognises every child's right to play and to recreational activities appropriate to age (Yogman et al., 2018). Nevertheless, the meta-analysis by Tomkinson et al. (2003) shows a rapid secular decline in 20 m shuttle-run performance among 6- to 19-year-olds over the past twenty years; similarly, Dordel (2000) reports a regression in coordinative abilities among primary-school children compared with peers from the 1970s. To clarify the link between PA and bio-psycho-social well-being, the systematic review by Poitras et al. (2016) documents favourable associations of PA with adiposity, cardiometabolic biomarkers, fitness, bone health, quality of life, motor-skill development and reduced psychological distress.

World Health Organization guidelines (WHO, 2020) recommend that children and adolescents (5–17 years) engage in at least 60 minutes of moderate-to-vigorous physical activity (MVPA) per day, predominantly aerobic throughout the week, together with muscle- and bone-strengthening exercises at least three times per week and systematic reduction of screen time. Yet the majority of children and adolescents do not achieve these levels (Tremblay et al., 2016), and more recent studies indicate further growth in non-compliance (Faigenbaum et al., 2018). The result is a generation of young people with lower strength and speed and

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higher body weight than in the past, a trend increasingly discussed in specialist paediatrics in relation to rising physical, psychosocial and cognitive disorders (Poitras et al., 2016).

In this context, the concept of physical literacy (PL) assumes particular importance; it represents an educated state of an individual's capacities and the ability to integrate and enhance them. Whitehead contributed substantially to defining this concept and, in 2001, described it as "*the ability to use one's body with skill, effectiveness and pleasure in a variety of contexts. It is the ability to move efficiently, safely and in control, and to utilise one's physical capacities to achieve goals, enjoy oneself and participate actively in life*" (Whitehead, 2001). She subsequently elaborated a five-component model of PL that includes knowledge of one's body and its capacities, competence understood as the safe and effective execution of movements, motivation to engage in PA and remain active, social skills aimed at interacting and collaborating with others and cultural skills, which involve understanding the historical, philosophical and artistic aspects of physical practice (Whitehead, 2010).

Consistent with these principles, the International Physical Literacy Association (IPLA, 2017) points out that motivation, confidence, physical competence, knowledge and understanding are fundamental to promoting a physically active lifestyle across the life course. From this perspective, PL is decisive in young people's holistic development, as it not only provides the foundations for active participation in a variety of physical activities but also fosters understanding of key concepts related to movement and health. According to Lander et al. (2015), PL encompasses motor competence, knowledge of the principles and practices of physical activity and the capacity to integrate these aspects in order to lead an active and healthy life.

A relevant aspect concerns the complex nature of PL, in which motor learning and development unfold through continuous processes of organising and reorganising movements aimed at achieving functional performance (Davids et al., 2023). Such dynamics are not always understood or exploited in teaching-learning contexts, especially in physical-education programmes and extracurricular activities. In many cases, attention focuses only on the development of simple movement capacities such as balance, basic coordination, core stability, flexibility or proprioception, neglecting to combine these skills into more complex and integrated forms such as bilateral coordination, inter-limb coordination, eye–hand coordination, control of accelerations and decelerations or rhythmic movements (Whitehead, 2010).

Understanding these constructs and related variables can inspire more effective intervention strategies aimed at promoting physical competence in young people. It is indeed possible to design appropriate practice opportunities and an environment conducive to PA (Minghelli et al., 2023; O'Brien et al., 2013), as well as assessment tools for physical competence that enable practitioners to monitor and evaluate the effectiveness of interventions (Castelli et al., 2014), thus going beyond the mere quantification of motor skills (Romano et al., 2023).

The *Test of Gross Motor Development* (TGMD-3) is a standardised instrument for assessing the level of development of gross-motor skills in children aged 3 to 11 years, highlighting strengths and weaknesses in view of potential educational or personalised actions (Ulrich et al., 2023). The first version of the test (TGMD) was published in 1985 (Ulrich & Sanford, 1985) to fill an evident gap in assessing motor development in childhood, offering examiners a rapid method for collecting data relevant to key educational decisions. In 2000 a new edition (TGMD-2) was released, introducing important changes following the revisions by Bunker and Edwards. Although recognising the TGMD's exceptional utility in identifying children with gross-motor weaknesses, they pointed out some sampling issues and the need for finer differentiation between boys and

girls. Finally, Dale Ulrich published the third version (TGMD-3) in 2019, incorporating further user feedback (Ulrich et al., 2023).

The TGMD-3 can be used to identify children who are significantly delayed relative to their peers, to plan instructional programmes targeting gross-motor development, to monitor individual progress, to evaluate the success of specific interventions and to support research into motor development. The instrument includes two subtests: one for locomotor skills (run, forward gallop, one-leg hops, skip, standing long jump, slide) and one for ball-control skills. Comparisons of raw scores with normative values yield scaled scores, percentile ranks and additional descriptors (ranging from "*poor or delayed*" to "*very advanced*"), while the sum of the two subtests' scaled scores provides the Gross Motor Index, which reflects the child's overall level of gross-motor development. It should be noted that the Italian manual of the TGMD-3 (Ulrich, 2023), unlike the U.S. version, provides gender-specific norms for the locomotor subtest, thereby improving the accuracy of comparisons with the Italian reference population.

The present study sets out to evaluate quantitatively how different forms of motor participation influence the locomotor skills of primary-school children, addressing three main questions. The first concerns the main effect of Structured Physical Activity (SPA): the aim is to verify whether regular participation in organised sports (irrespective of discipline) is associated with higher TGMD-3 locomotor subtest scores than non-participation. The second question pertains to the contribution of Unstructured Physical Activity (UPA) and the possible interaction between SPA and UPA, in order to determine whether spontaneous motor activity during free time further increases locomotor scores and whether a joint effect exists between these variables. Finally, the third question examines the impact of the type of sport practised, analysing whether the open-skill (variable environment) or closed-skill (stable environment) nature of a sport modifies locomotor-skill levels. In summary, the study aims to quantify the main and combined effects of SPA, UPA and sport type on the TGMD-3 locomotor score, providing evidence of their importance for motor development in school-age children.

MATERIALS AND METHODS

Participants

The sample comprised 148 pupils (mean age = 8.7 ± 0.7 years), of whom 77 were girls and 71 boys. They were drawn from the third (n = 73) and fourth (n = 75) grades of a primary school located in a predominantly rural municipality in southern Italy (<10 000 inhabitants). All pupils were involved in a school-year physical-activity project. Inclusion criteria were regular school attendance and voluntary participation in the project; a history of traumatic events with potential impact on motor performance constituted an exclusion criterion.

The study protocol received formal authorisation from the school leadership and approval from the University Department Ethics Committee (Protocol no. 0125702). The research was designed and coordinated by the Laboratory for Innovative Teaching and Sports Performance Analysis at the University of Salerno (UNISA) and was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki and relevant national regulations. Parents or legal guardians of every participant provided written informed consent, and data anonymity was guaranteed. All assessments were carried out in the school building, during school hours, under standardised environmental and organisational conditions.

Each pupil was told in simple terms the purpose of the activities (presented as "*movement games to see how you move*"), and the examiner spent a few minutes establishing a positive, reassuring rapport to reduce

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evaluation anxiety. Before testing, a supervised warm-up of ten minutes of light running and guided joint-mobility exercises was performed to lessen muscle stiffness and injury risk.

The locomotion subtest of the Test of Gross Motor Development – Third Edition (TGMD-3, Italian version) was administered; it requires six fundamental skills (run, forward gallop, one-leg hops, skip, standing long jump and slide). The standardised TGMD-3 instructions were read verbatim, and only neutral encouragement ("*keep going*", "*try again*") was offered, without technical hints. After a practical demonstration by the examiner, each pupil completed one unscored practice trial to confirm understanding; when necessary, a second demonstration was provided before starting the test proper (Ulrich et al., 2023). Each pupil then performed two scored trials per skill, all video-recorded for later scoring. Testing was organised in two separate sessions, with the sample divided and video-recording used to speed execution and facilitate later analysis. The videos were subsequently analysed to score performance criteria, minimising observation errors.

In this study, limited to the locomotion subtest, raw scores were converted into age- and sex-normalised scaled scores. The TGMD-3 manual recommends this equal-interval metric because it allows locomotor abilities to be assessed separately from the normative sample and highlights individual strengths and weaknesses (Ulrich et al., 2023). These properties made the scaled score the most appropriate measure for the planned analyses. Using standardised scores is also consistent with applied literature on motor development (Barnett et al., 2009). For communicative clarity, each scaled score was additionally translated into the seven official descriptive levels, providing results in an immediately understandable format without sacrificing statistical rigour (Ulrich et al., 2023).

After the motor tests, pupils completed a paper questionnaire documenting their physical and sports habits and distinguishing between:

1. Structured Physical Activity (SPA): organised sport, that is, exercise directed by a coach or responsible adult, governed by formal rules and structured training sessions, often including competition (Marques et al., 2016; Chen et al., 2020). To be classified as SPA, the activity had to be practised at least four times per week (each session ≥ 60 minutes) for a minimum of four consecutive months. Children indicated the discipline (e.g., football, basketball, dance, swimming, martial arts), the number of weekly training sessions, regularity and overall duration of participation.
2. Unstructured Physical Activity (UPA): non-structured physical activity carried out outdoors during free time (Brockman et al., 2011) at least four times per week. This category included outdoor games (e.g., free running, ball games), walking or cycling, and other forms of movement not guided by an instructor. Children also reported the average duration of these activities and the consistency with which they were practised.

Analysis

All TGMD-3 data (raw scores and subsequent scaled scores) and the information obtained from the questionnaire (SPA and UPA) were merged into a single digital file (Excel). This integration made it possible to correlate locomotor-skill level with the different forms of motor participation, in line with the objectives of the present study.

All analyses were conducted in Python 3.11 (Pandas 2.2.0, SciPy 1.11.4, Statsmodels 0.14); the significance threshold was set at $\alpha = .05$, and all tests were two-tailed. First, to describe the full sample of 148 children, the mean, standard deviation, median and range of the TGMD-3 locomotor scaled score were calculated; these values were then re-classified into the seven international descriptive categories, and absolute and

percentage frequencies were reported. To explore the distribution of categorical variables, contingency tables were produced crossing participation in Structured Physical Activity (SPA: organised sport yes/no), type of sport practised (open-skill vs closed-skill) and the presence of Unstructured Physical Activity (UPA). The category "*absence of UPA*" also includes the eight totally inactive subjects.

Before proceeding with inferential tests, normality of the scaled-score distribution was assessed with the Shapiro–Wilk test, and homogeneity of variances with Levene's test. Because moderate violations of these assumptions appeared in some sub-groups, the Welch version of parametric tests was adopted, as it is suitable when variances and sample sizes are unequal. The main effect of SPA was estimated with a Welch t-test, reporting the t value, p value, 95 % confidence interval of the mean difference and effect size (Cohen's d). The same approach was used to compare the scores of open-skill versus closed-skill athletes; in that case the point-biserial coefficient r_{pb} was also calculated. The same coefficient was estimated for the SPA versus non-SPA comparison (UPA-only + inactive) in order to quantify the association between the respective binary variables and locomotor performance.

To investigate the joint action of SPA and the group "*UPA-only + inactive*", a 2 × 2 factorial ANOVA was run via OLS regression, including SPA, the UPA-only + inactive indicator and their interaction term as predictors. Coefficients were tested with Type-II F tests and, for each effect, partial η^2 was reported. As no significant interaction emerged, a Tukey HSD post hoc on the four resulting combinations was nonetheless applied, controlling familywise error; all contrasts returned $p > .35$. For exploratory purposes, the means of the four mutually exclusive sub-groups resulting from the full SPA × UPA cross (SPA + UPA, SPA-only, UPA-only, inactive) were compared via a one-way Welch ANOVA; the global test was not significant ($p = .124$), but, for completeness, the planned contrast between SPA-only and UPA-only is reported with the corresponding Welch t, confidence interval and Cohen's d. Relationships between continuous variables were examined with Pearson correlations, whereas continuous-binary pairings were assessed with point-biserial correlations, both accompanied by 95 % confidence intervals. Missing data, amounting to less than 5 % of the total, were handled by list-wise deletion; multivariate outliers were checked using Mahalanobis distance (χ^2 cut-off, $p < .001$), with no further exclusions required.

This combination of precise descriptive statistics, robust tests and multifactorial models provides a reliable assessment of the effects of SPA, UPA and sport type on TGMD-3 locomotor scores in the sample under investigation.

RESULTS

Sample distribution

In the descriptive analysis, the mean scaled score on the TGMD-3 locomotor sub-test was 8.23 ± 2.68 (median = 9; range = 1–14) for the whole sample. The TGMD-3 locomotor scores were reclassified into seven descriptive categories: Impaired or Delayed, Borderline Impaired or Delayed, Below Average, Average, Above Average, Superior, and Gifted or Very Advanced. Table 1 summarises the distribution of these categories in the third-grade group (n = 73; Fig. 1), the fourth-grade group (n = 75; Fig. 2), and in the total sample. In both grades the most frequent category was Average, and no participant reached the highest categories (Superior or Gifted or Very Advanced). Considering all 148 participants, 95 children (64.2 %) were classified as Average, 25 (16.9 %) as Borderline Impaired or Delayed, 17 (11.5 %) as Below Average, 8 (5.4 %) as Impaired or Delayed, and 3 (2.0 %) as Above Average.

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Table 1. Distribution of Grade 3 and Grade 4 children across the seven TGMD-3 locomotor descriptive categories. Columns list absolute counts for each grade, overall totals, and the percentage that each level represents within the entire sample (n = 148).

Descriptive category	Grade 3	Grade 4	Total	Percentage of the sample (n = 148)
Impaired or Delayed	2	6	8	5.4 %
Borderline Impaired or Delayed	14	11	25	16.9 %
Below average	10	7	17	11.5 %
Average	46	49	95	64.2 %
Above average	1	2	3	2.0 %
Superior	0	0	0	0 %
Gifted or Very Advanced	0	0	0	0 %
Total	73	75	148	—

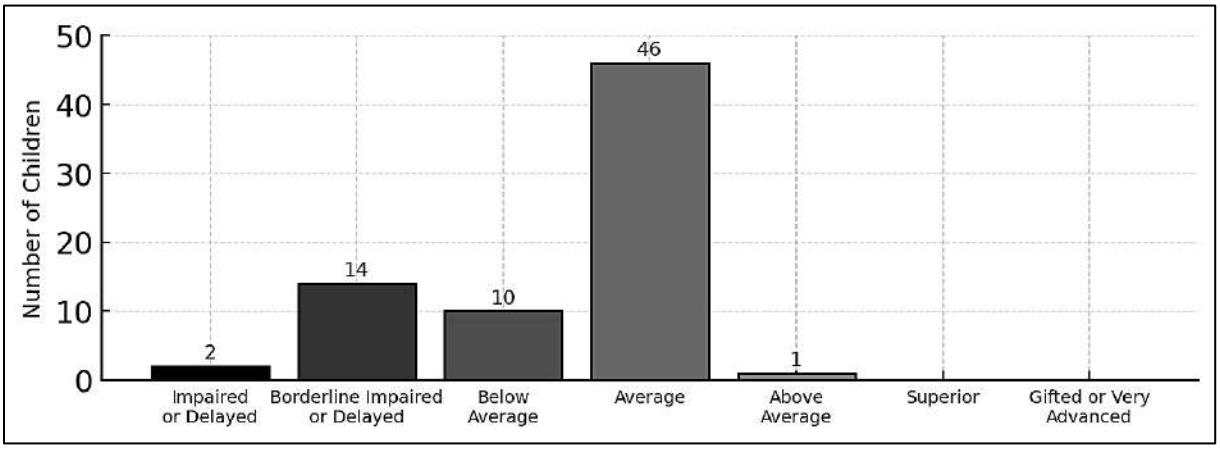

Figure 1. Absolute frequency distribution of third-grade children (N = 73) across the seven TGMD-3 locomotor descriptive categories, ordered from Impaired or Delayed to Gifted or Very Advanced. The y-axis ranges from 0 to 50; most children fell in the Average category (n = 46), while none reached the Superior or Gifted or Very Advanced categories.

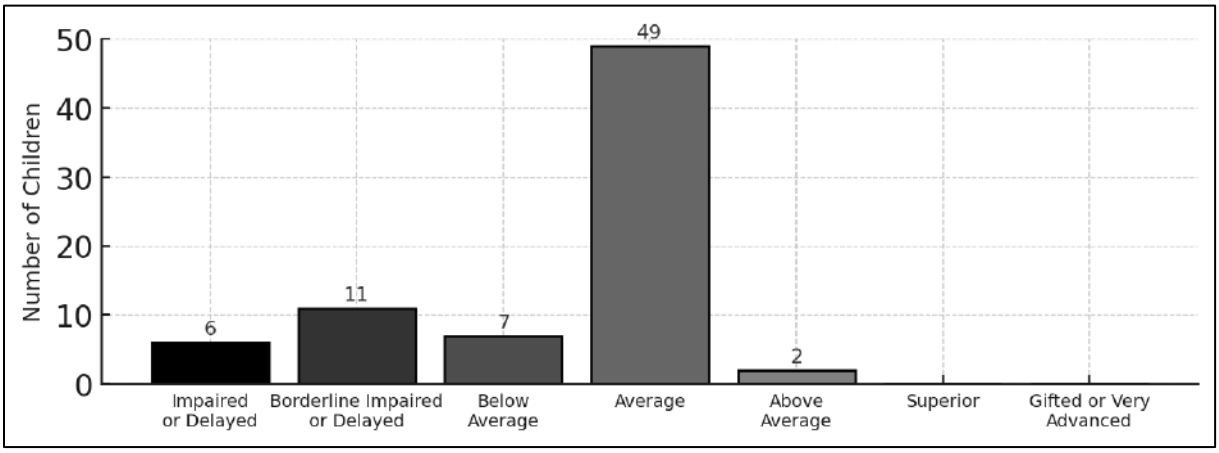

Figure 2. Absolute frequency distribution of fourth-grade children (N = 75) across the seven TGMD-3 locomotor descriptive categories, ordered from Impaired or Delayed to Gifted or Very Advanced. The y-axis ranges from 0 to 50; the predominant category was Average (n = 49), and, as in Grade 3, no child reached the Superior or Gifted or Very Advanced categories.

With regard to motor practice, 54.7 % of the sample (n = 81) took part in Structured Physical Activity (SPA): forty-seven children engaged in open-skill sports (31.8 % of the total) and thirty-four in closed-skill sports (23.0 %). The remaining 45.3 % (n = 67) did not practise any organised sport. Regardless of SPA participation, 86.5 % of the pupils (n = 128) reported performing Unstructured Physical Activity (UPA) in their leisure time. In the remaining 13.5 % (n = 20) no UPA was reported: twelve of these children nevertheless engaged in a structured sport, whereas eight were inactive (neither SPA nor UPA) outside school hours (Fig. 3). Table 2 summarises, for these four subgroups, the sample size together with the mean and the standard deviation of the TGMD-3 locomotor scaled score.

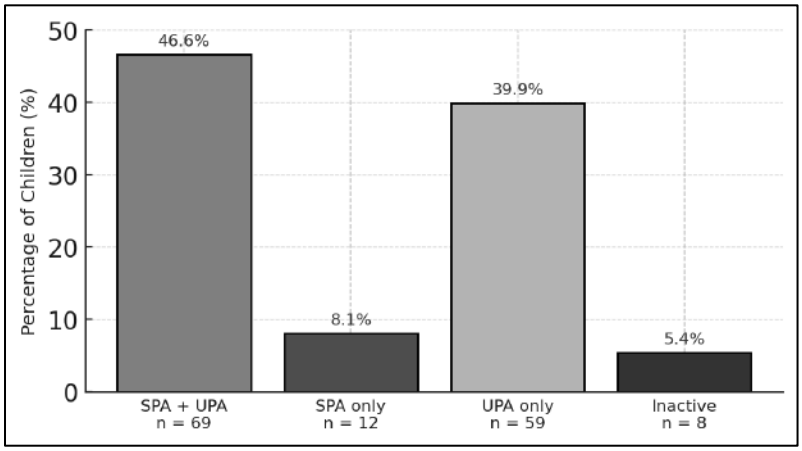

Figure 3. The whole sample (N = 148) is split into four mutually-exclusive physical-activity categories: Structured Physical Activity (SPA) + Unstructured Physical Activity (UPA), SPA only, UPA only, and Inactive (neither SPA nor UPA).

Table 2. Distribution of mean (± SD) TGMD-3 locomotor scaled scores across the four mutually exclusive subgroups obtained by cross-classifying Structured Physical Activity (SPA) with Unstructured Physical Activity (UPA).

Group (SPA / UPA)	Numbers	Mean ± SD (points)
No-SPA / No-UPA (Inactive)	8	7.38 ± 2.07
UPA-only	59	7.78 ± 2.59
SPA-only	12	9.17 ± 1.99
SPA / UPA	69	8.55 ± 2.86

Table 3. Distribution of the 81 children engaged in Structured Physical Activity (SPA) across the five TGMD-3 locomotor categories, split by open-skill and closed-skill sports. Values are counts with row percentages in parentheses; the last row presents the overall totals for each category.

SPA	Impaired or delayed n (%)	Borderline impaired or delayed n (%)	Below average n (%)	Average n (%)	Above average n (%)	Total n
Open-skill	2 (4.3)	4 (8.5)	9 (19.1)	29 (61.7)	3 (6.4)	47
Closed-skill	2 (5.9)	5 (14.7)	3 (8.8)	24 (70.6)	0 (0.0)	34
Total	4 (4.9)	9 (11.1)	12 (14.8)	53 (65.4)	3 (3.7)	81

Restricting the observation to athletes only (n = 81), Table 3 shows that open- and closed-skill sports display similar profiles: in the former, 29 of 47 participants (61.7 %) fell into the Average category and 3 (6.4 %) into the Above Average category; in the latter, 24 of 34 participants (70.6 %) were classified as Average and none

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as Above Average. Overall, the athlete group included 4 children in the Impaired or Delayed category (4.9 %), 9 in the Borderline Impaired or Delayed category (11.1 %), 12 in the Below Average category (14.8 %), 53 in the Average category (65.4 %), and 3 in the Above Average category (3.7 %).

Table 4 cross-tabulates sport type with UPA. Almost half of the athletic subsample comprised children who engaged in Open + UPA activities (n = 40; 49.4 %); they were followed by those involved in Closed + UPA (n = 29; 35.8 %), whereas groups with no UPA were numerically small (Open + No-UPA: 7 children, 8.6 %; Closed + No-UPA: 5 children, 6.2 %). Within these four combinations, the Average category remained the most frequent: among the Open + UPA group, 24 children (29.6 % of the athletic subsample) fell into this category; similarly, 19 children in the Closed + UPA group (23.5 %) reached the same level. Extreme categories were rare: in total, only 4 participants (4.9 %) were classified as Impaired or Delayed and 3 (3.7 %) as Above Average.

Table 4. Distribution of the 81 children who practise organised sport across the five TGMD-3 locomotor descriptive categories, cross-classified by sport type (open-skill vs closed-skill) and by whether they also engage in Unstructured Physical Activity (UPA). Values are counts with row percentages in parentheses; the final row presents the overall totals for each category.

SPA	UPA	Impaired or delayed n (%)	Borderline impaired or delayed n (%)	Below average n (%)	Average n (%)	Above average n (%)	Total n (%)
Open-skill	Yes	2 (2.5)	3 (3.7)	8 (9.9)	24 (29.6)	3 (3.7)	40 (49.4)
Open-skill	No	0 (0.0)	1 (1.2)	1 (1.2)	5 (6.2)	0 (0.0)	7 (8.6)
Closed-skill	Yes	2 (2.5)	5 (6.2)	3 (3.7)	19 (23.5)	0 (0.0)	29 (35.8)
Closed-skill	No	0 (0.0)	0 (0.0)	0 (0.0)	5 (6.2)	0 (0.0)	5 (6.2)
Total	—	4 (4.9)	9 (11.1)	12 (14.8)	53 (65.4)	3 (3.7)	81 (100)

Comparison between SPA and UPA-only + inactive in TGMD-3 locomotor scores

When children who engaged in SPA were compared with peers who did not take part in structured sport (UPA-only + inactive), a mean advantage of 0.91 scaled points emerged in favour of the SPA group (Table 5). The SPA group, comprising 81 children involved in both open- and closed-skill disciplines, included every participant who performed at least one structured activity, regardless of any Unstructured Physical Activity (UPA), and showed a mean score of 8.64 ± 2.74. The UPA-only + inactive group (n = 67) consisted of 59 pupils who participated solely in UPA and eight who were inactive (neither SPA nor UPA); their combined mean was 7.73 ± 2.53. Welch's t-test confirmed that this difference was significant ($t \approx 2.10$; $p = .038$); the 95 % confidence interval for the mean difference (0.05 – 1.77) did not include zero.

The effect size, calculated as Cohen's d = 0.34, fell within the small-to-medium range. The point-biserial correlation between SPA membership (1 = yes, 0 = no) and the TGMD-3 score was r_{pb} = 0.17 ($p = .039$), accounting for roughly 3 % of the explained variance.

Table 5. Comparison of TGMD-3 locomotor scaled scores between children engaged in Structured Physical Activity (SPA) and age-matched peers who do not practise structured sport (UPA-only + inactive). The n column gives group size; Mean ± SD shows the mean with standard deviation; Cohen's d is the effect size; r_{pb} is the point-biserial correlation with its corrected p value; Mean difference reports the SPA–control difference with a 95 % confidence interval; p (t-test) is the Welch t-test *p*-value.

Group	n	Mean ± SD	Cohen's d	rpb	*p* (corr.)	Mean difference (95% CI)	*p* (t-test)
SPA	81	8.64 ± 2.74	—	—	—	—	—
UPA-only + inactive	67	7.73 ± 2.53	—	—	—	—	—
Total / test	148	—	0.34	0.170	.039	+0.91 pt (0.05 – 1.77)	.038

Factorial analysis of SPA and UPA in TGMD-3 locomotor scores

To examine the combined effect of Structured Physical Activity (SPA) and the UPA-only + inactive condition on the TGMD-3 locomotor score, a 2 × 2 factorial analysis was performed. Structured Physical Activity was defined as every child who engaged in at least one structured motor activity (SPA-only or SPA + UPA); the second factor identified children who either practised only Unstructured Physical Activity (UPA) or were inactive.

The analysis revealed a single significant effect: the presence of SPA. The SPA factor accounted for roughly 3 % of the variance in the TGMD-3 locomotor score (SS = 31.61; F = 4.47; p = .036; partial η^2 = 0.030). By contrast, the comparison between children who performed only UPA and/or were inactive and those who did not yielded no significant differences (SS = 0.86; F = 0.12; p = .728; partial $\eta^2 \approx 0.001$); nor did any SPA × (UPA-only + inactive) interaction emerge (SS = 2.81; F = 0.40; p = .530; partial $\eta^2 \approx 0.003$).

Because the SPA × UPA interaction was not significant (p = .53), the UPA levels were collapsed into a single category. Children who practised any Structured Physical Activity (n = 81) were compared with peers without SPA (n = 67), revealing an average advantage of 0.9 scaled points (d = 0.34) in favour of the former.

The group UPA-only + inactive therefore represented both children who engaged solely in spontaneous motor activity and those who were completely inactive. As shown in Table 2, subgroups without SPA (whether with or without UPA) scored around 7.4–7.8 scaled points, whereas children with SPA scored 8.6–9.2, regardless of their unstructured-activity level. The absence of interaction and the non-significant post-hoc tests (Tukey HSD, all p > .35) confirmed the lack of differential effects among groups not involved in structured activities.

Table 6. 2 × 2 ANOVA for the TGMD-3 locomotor scaled score with the factors Structured Physical Activity (SPA) and UPA-only + inactive (children who perform only Unstructured Physical Activity or are inactive, i.e., neither SPA nor UPA). Partial η^2 = SS / (SS + SS_{Residual}).

Effect	SS	df	F	*p*-value	Partial η^2
SPA	31.61	1	4.47	.036	0.030
UPA-only + INACTIVE	0.86	1	0.12	.728	0.001
SPA × (UPA-only + INACTIVE)	2.81	1	0.40	.530	0.003
Residual	1 018.65	144	—	—	—

To assess differences among the four subgroups created by crossing Structured Physical Activity (SPA: yes / no) and Unstructured Physical Activity (UPA: yes / no) on the TGMD-3 scaled score, a four-level Welch ANOVA was conducted. This test, chosen because of unequal variances and sample sizes, revealed no overall significant differences (F(3, 25.08) = 2.11, p = .124; see Table 7).

The planned comparison between SPA-only (n = 12) and UPA-only (n = 59) showed a mean advantage of 1.39 points for the SPA-only group; Welch's t-test (t(19.45) = 2.08, p = .051) and the 95 % confidence interval (–0.01 – 2.78) indicated that this difference did not reach statistical significance. The effect size was moderate (Cohen's d = 0.55).

Preliminary checks showed slight non-normality in the No-SPA / No-UPA group (Shapiro–Wilk W = 0.83, p = .065) and in the SPA + UPA group (W = 0.95, p = .012), whereas variances were homogeneous (Levene F = 1.35, p = .260), supporting the use of Welch versions of ANOVA and t-tests.

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Table 7. Comparison of the TGMD-3 scaled score across the four subgroups obtained by crossing Structured Physical Activity (SPA) and Unstructured Physical Activity (UPA). The "*Comparison*" column presents the results of the four-level Welch ANOVA and, at the bottom, the planned SPA-only vs UPA-only contrast (mean difference, Welch t, *p*-value and effect size).

Statistic	No-SPA / No-UPA (Inactive, n = 8)	UPA-only (n = 59)	SPA-only (n = 12)	SPA + UPA (n = 69)	Comparison
Mean ± SD (points)	7.38 ± 2.07	7.78 ± 2.59	9.17 ± 1.99	8.55 ± 2.86	—
Welch ANOVA					F(3, 25.08) = 2.11, *p* = .124
Mean difference (SPA-only – UPA-only)					+1.39 pt (95% CI = -0.01 – 2.78)
t (Welch, df ≈ 19.45)	—	—	—	—	2.08
p (t-test)	—	—	—	—	.051
Cohen's d	—	—	—	—	0.55

Comparison between open- and closed-skill sports in TGMD-3 locomotor scores

The comparison between participants engaged in open-skill disciplines (n = 47) and those in closed-skill disciplines (n = 34) revealed no significant differences in the TGMD-3 locomotor scaled score (Table 8). The open-skill group averaged 8.83 ± 2.85 points, whereas the closed-skill group averaged 8.38 ± 2.61 points; the mean gap of 0.45 points was not significant (Welch's t(≈ 75) = 0.733, *p* = .466; 95 % CI = –0.77 to 1.66). The effect size was small (Cohen's d = 0.16), and the point-biserial correlation between sport type and score was modest and non-significant (r_{pb} = 0.08, *p* = .472).

Preliminary tests confirmed the appropriateness of the procedure: Shapiro–Wilk indicated slight non-normality in the closed-skill group (W = 0.89, *p* = .002) but not in the open-skill group (W = 0.96, *p* = .108), while Levene's test showed equal variances (F = 0.52, *p* = .472). Under these conditions, the Welch t-test yielded a robust estimate of the mean difference.

Table 8. Comparison of TGMD-3 locomotor scaled scores between open-skill sports (n = 47) and closed-skill sports (n = 34). Shown are the group means ± SD, the mean difference with its 95 % confidence interval, Welch's t (df ≈ 75), the associated *p*-value, effect size (Cohen's d) and point-biserial correlation (r_{pb}).

Statistic	Open-skill (n = 47)	Closed-skill (n = 34)	Comparison
Mean ± SD (points)	8.83 ± 2.85	8.38 ± 2.61	—
Mean difference (Open – Closed)	—	—	+0.45 pt (95% CI = –0.77 – 1.66)
t (Welch, df ≈ 75)	—	—	0.733
p (t-test)	—	—	.466
Cohen's d	—	—	0.16
rpb	—	—	0.08 (*p* = .472)

DISCUSSION

The mean score on the TGMD-3 locomotor subtest (8.23 ± 2.68) and the strong concentration at the Average level (64.2 %) indicate that most of the sample exhibits average locomotor competence. The rather wide range (1–14) nonetheless reveals substantial inter-individual variability. In the rural context examined, the limited availability of sports facilities and structured programmes (Gallotta et al., 2022) may hinder motor development and favour weight gain. At the same time, the low population density provides ample green spaces and lightly trafficked roads that encourage free play: Stojiljković et al. (2025) show that, in similar settings, spontaneous outdoor activity is more widespread and partly offsets the lack of organised opportunities. In the present sample, 54.7 % of children take part in Structured Physical Activity (SPA) and 86.5 % report Unstructured Physical Activity (UPA); only 5.4 % are completely inactive. These data reiterate

the importance of promoting SPA participation from early childhood to counteract sedentary behaviour and obesity (Bouchard et al., 2012; Mazur et al., 2018, cited in Colella & Vera, 2020).

The main effect of SPA is clear: children involved in organised sports score on average 0.91 scaled points higher than peers without SPA (Cohen's d = 0.34; $p \approx .038$). Consistent with numerous studies (McNeill et al., 2018; Iivonen & Sääkslahti, 2014; Strong et al., 2005), the finding confirms the role of structured programmes in enhancing fundamental skills. Multifactorial analysis shows that the SPA × (UPA-only + inactive) combination produces no significant interaction: spontaneous activity alone does not raise the TGMD-3 score, nor does it amplify the positive effect of organised sport (Donnelly et al., 2016; Poitras et al., 2016). When the goal is to develop specific motor competences, systematic training guided by qualified coaches therefore remains crucial (Iivonen & Sääkslahti, 2014).

The comparison between open-skill and closed-skill disciplines reveals no significant differences ($p \approx .466$; d = 0.16). At eight–nine years of age, it is plausible that the quality of motor activity—encompassing coordinative drills, basic patterns and adequate supervision—matters more than the open or closed nature of the sporting context (Castelli et al., 2007). Overall, the small effect size and modest point-biserial correlation (r_{pb} = 0.08) suggest that differences linked to sport type might emerge only with larger samples or at ages when specialisation is greater.

The evidence collected strengthens the call for targeted school interventions and high-quality extracurricular programmes (Piggin, 2020; Caspersen et al., 1985). This aligns with Whitehead's (2010) Physical Literacy paradigm, according to which solid motor foundations and self-awareness in movement foster an active lifestyle across the life span. Because childhood sedentariness is associated with cardiometabolic risk and overweight (Guthold et al., 2020; Mazur et al., 2018), it is essential to ensure at least 60 minutes per day of moderate-to-vigorous activity, as recommended by the WHO (2020). The results confirm that participation in organised sports, whether open-skill or closed-skill, is conducive to higher locomotor-skill levels, whereas spontaneous activity alone appears less effective in improving TGMD-3 scores. This underlines the need for physical-literacy pathways from primary school onwards to promote balanced motor development and lasting active habits.

CONCLUSION

The results obtained suggest that structured physical activity (SPA) plays a fundamental role in the development of locomotor skills during the school years. These findings align with the existing literature, which underscores the centrality of organised, systematic practice for fostering the acquisition of essential motor competences (Iivonen & Sääkslahti, 2014; Strong et al., 2005). Nevertheless, while acknowledging the efficacy of SPA, it remains important not to underestimate the value of unstructured physical activity (UPA), which nonetheless contributes to overall health and to a long-term disposition toward an active lifestyle.

In the rural context investigated, 86.5 % of the children engage in UPA; this unusually high percentage confirms that green spaces, limited traffic and strong neighbourhood ties favour spontaneous outdoor play, simultaneously offering a key opportunity for community-based physical-activity promotion policies. It is likely, however, that the UPA finding in this study was affected by the intrinsic difficulty of accurately quantifying and assessing this type of activity, whose importance is clearly supported by the literature. Because UPA is, by definition, unsupervised and variable, it eludes objective recording of frequency, intensity and quality: children's self-reports may therefore under- or overestimate the actual motor load, attenuating statistical associations with outcomes. As stated in the WHO Global Action Plan on Physical Activity (GAPPA) 2018–

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2030, the goal is to guarantee everyone access to diverse movement opportunities, thereby reducing physical inactivity by 15 % by 2030 (WHO, 2019). This target relates directly to the concept of Physical Literacy (PL), which helps explain the complex factors that shape lifelong physically active individuals (Carl et al., 2023).

The practical implications of this study are numerous and significant. First, it is clear that schools constitute a privileged setting for reaching children and effectively promoting a physically active lifestyle. Consequently, teachers must receive appropriate training, acquiring specific competences to design and deliver structured motor activities that integrate the core elements of Physical Literacy. It should also be borne in mind that the TGMD-3 locomotor subtest items mirror exercises widely used in many organised sports; children engaged in SPA may therefore have enjoyed a "*familiarity advantage*" over peers who practise only UPA, contributing to the score differences observed.

Equally important is the reminder that pragmatically measuring the specific elements constituting PL should not entail imposing rigid parameters or absolute standards but rather providing researchers and practitioners with tools to design targeted, flexible physical-literacy pathways that meet children's diverse needs and promote holistic physical activity encompassing all aspects of PL itself (Britton et al., 2023).

This study has certain limitations, foremost among them the exclusive analysis of the TGMD-3 locomotor subtest. Including the object-control subtest would have offered a broader and more complete picture of children's motor development, enabling an integrated assessment of gross-motor competences. A further consideration concerns UPA: beyond the measurement challenges already discussed, future studies should integrate objective instruments capable of capturing not only the intensity and duration of activity but also its quality, modes of execution and contextual settings. Such an approach could yield deeper insight into UPA's role in children's motor development. Finally, future work should extend the analysis to larger samples that are geographically and socio-culturally diverse, incorporating non-rural contexts such as urban and peri-urban areas; moreover, the qualitative influence of structured programmes should be evaluated, and the interaction between structured and unstructured physical activity on the various dimensions of children's motor and cognitive development explored.

AUTHOR CONTRIBUTIONS

The article is the result of collaborative work by all the authors. Rodolfo Vastola is the Scientific Coordinator of the entire contribution.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

ETHICAL APPROVAL

The present study has been approved by the University Department Ethics Committee of the University of Salerno (protocol no. 0125702).

DATA AVAILABILITY STATEMENT

Data available on request.

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ORIGINAL ARTICLE

Sports biomechanical analysis of international Standard Dance: Movement techniques in Standard Dance

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ABSTRACT

As a principal discipline within International Standard Dance, Standard Dance requires dancers to possess strong body control capabilities and a profound understanding of sports biomechanics due to the complexity of its technical movements and the demands for artistic expressiveness. This study adopts a sports biomechanical perspective, employing expert surveys, video analysis, and interdisciplinary research methods to investigate the fundamental techniques of Standard Dance—specifically rise and fall, weight transfer, contra body movement, swing, inclination, and rotation—with the aims of exploring the biomechanical principles underlying these techniques and their practical application in dance movements. The research findings indicate that the movement techniques of Standard Dance adhere to the fundamental principles of sports biomechanics. Specifically, the "*S*"-shaped kinetic chain transmission sequence in rise-and-fall techniques optimizes energy transfer efficiency, the dynamic balance control mechanism in weight transfer enhances dancers' stability, the conservation of angular momentum in contra body movement provides a mechanical foundation for rotational actions, the regulation of muscular torque in inclination techniques maintains dynamic equilibrium, the conversion between potential and kinetic energy in swing techniques enhances dance fluidity and artistic expressiveness, and the transfer of angular momentum in rotation techniques offers mechanical support for the execution of complex rotational movements. This study employs sports biomechanical principles to analyse the six core techniques of Standard Dance, revealing the biomechanical mechanisms underlying movement efficiency and artistic expressiveness, thereby providing a crucial theoretical foundation for the scientific refinement and precision-oriented optimization of technical training.

Keywords: Biomechanics, International Standard Dance, Sports biomechanics, Movement techniques.

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INTRODUCTION

International Standard Dance is a standardized and procedural athletic discipline performed by male-female couples. It requires the precise demonstration and application of physical techniques and skills within defined musical and rhythmic parameters, combined with artistic expression to create a cohesive performance (Li, 2015). As a sport that integrates artistic and competitive elements, International Standard Dance adheres to the principles of human biomechanics. It achieves its unique movement dynamics through the harmonious coordination of body actions, music, and spatial trajectories (Sofron & Tifrea, 2022). As a principal discipline within International Standard Dance, Standard Dance encompasses five distinct styles: Waltz, Tango, Viennese Waltz, Foxtrot, and Quickstep (World Dance Sport Federation, 2023). Its technical execution necessitates not only intricate neuromuscular coordination and dynamic equilibrium control but also requires dancers to sustain refined artistic expression amidst high-velocity movement sequences.

Driven by the continuous elevation of competitive benchmarks and groundbreaking advancements in human movement science, research in International Standard Dance pedagogy and training methodologies is undergoing a paradigm shift toward interdisciplinary integration. Examples include employing sports biomechanical principles to analyse and optimize movement mechanics (Chang et al., 2019; Hanks et al., 2024; Song et al., 2020), utilizing exercise physiology metrics to refine training load management (Li et al., 2022; Zhang et al., 2022; Zhou et al., 2024), leveraging digital information technology to develop virtual reality-assisted training systems (Liu et al., 2023; Ni & Yao, 2021), and integrating medical theories to enhance sports injury prevention and assessment protocols (Liu et al., 2024; Liu et al., 2025). Collectively, these studies provide innovative perspectives for deconstructing technical principles, optimizing movement performance, and advancing technical proficiency.

Sports biomechanics, as a discipline that investigates the mechanical characteristics and laws governing living organisms during motion or under external forces, encompasses the study of human movement principles as one of its pivotal research domains. By analysing mechanical factors under diverse movement states, it provides a scientific foundation for enhancing athletic performance, optimizing training methodologies, and mitigating sports injuries. In recent years, the application of biomechanical principles in dance training has emerged as a prominent research focus. Relevant studies concentrate on movement optimization, energy efficiency enhancement, and injury prevention, with notable advancements achieved in dance genres such as ballet (Chung et al., 2023; Li et al., 2022; Thullier & Moufti, 2004) and modern dance (Farmer & Brouner, 2025; Torrents et al., 2013; Wilson & Kwon, 2008). Research on the application of sports biomechanics principles in standard dance training has also demonstrated a trend of increasing depth. Some scholars have conducted studies focusing on biomechanical analysis of standard dance techniques. For instance, Standard Dance practitioners rely more heavily on coordinated hip-knee-ankle movements during weight transfer (Yoshida et al., 2022). In the basic Waltz step, male dancers must withstand vertical ground reaction forces approximately 1.2 times their body weight to maintain the stability of the partner hold (Li, 2015). The correlation between dynamic stability and energy efficiency is particularly pronounced during dance step transitions (Kulis et al., 2023). Additionally, some scholars have investigated how to prevent sports injuries through the optimization of movement techniques. For instance, rise and fall movements rely on the coordinated flexion and extension of the knee and ankle joints, while requiring core muscle engagement to stabilize the torso. Excessive knee flexion increases patellofemoral joint pressure, leading to sports injuries (Premelč et al., 2019). Assessments of fall risk during rotational movements reveal that dancers exhibit significantly increased lateral displacement of the centre of pressure, which correlates with dynamic balance control capabilities (Yoshida et al., 2022).

Fundamental techniques represent the most characteristic and essential elements of Standard Dance, serving as the foundation for executing complex movements and demonstrating advanced dance skills. Although existing research has achieved notable progress in the biomechanical analysis of fundamental Standard Dance techniques, and scholars have widely acknowledged the critical importance of these foundational skills, the majority of studies remain confined to fragmented investigations of individual techniques. These studies lack a holistic analysis of the technical system and have yet to develop a coherent theoretical framework. Furthermore, existing research predominantly focuses on biomechanical analyses of techniques such as weight transfer (Chang et al., 2019; Liu & Deng, 2012), rise and fall (Shioya, 2016; Wang, 2021), and rotation (Prosen et al., 2013；Yoshida et al., 2022), while studies on contra body movement, inclination, and swing remain relatively scarce. Therefore, an in-depth exploration of the biomechanical principles underlying Standard Dance techniques is critical for understanding dancers' dynamic postural control, energy transfer efficiency, and multi-joint coordinative movements, while also providing theoretical support for coaches in the context of dancer training to optimize technical execution with precision, enhance competitive performance and artistic expression. This research offers direct scientific evidence and practical guidelines for the pedagogy and training of Standard Dance, thereby facilitating the transformation of International Standard Dance training from traditional experience-driven approaches to modern scientific paradigms.

METHODOLOGY

Expert survey method

Data sources

To comprehensively understand the fundamental technical system of Standard Dance, we systematically reviewed technical materials from the World DanceSport Federation (WDSF), as well as relevant literature and books on Standard Dance teaching and training. The study primarily relies on the technical classification outlined in the World DanceSport Federation Technique Books, which categorizes Standard Dance figures into three levels: Gold, Silver, and Bronze. The fundamental techniques consist of 12 elements, including weight transfer, rise and fall, swing, contra body movement, inclination, rotation, shoulder leading, extension, heel turn, twist, heel pull, and pivot (World Dance Sport Federation, 2013).

Analysis methods

To precisely define the scope of this study and further clarify the core content of Standard Dance fundamental techniques, a questionnaire survey was conducted with 10 authoritative experts in the field of International Standard Dance. The experts included university International Standard Dance instructors and certified judges. All university instructors held associate professor or higher positions with over 15 years of teaching experience, while the judges held international-level certifications. Each expert evaluated the inclusion of each technique as either "*approved*" or "*not approved*", with data recorded in binary format (1 for "*approved*", 0 for "*not approved*").

Additionally, to further assess the consistency of expert opinions, this study employs Gwet's AC1 coefficient for statistical analysis. Gwet's AC1 is a statistical method suitable for evaluating agreement among multiple raters across multiple categorical items, effectively measuring the level of consensus among experts regarding the recognition of Standard Dance fundamental techniques. The calculation of the Gwet's AC1 coefficient is based on the evaluation results of each technique by the experts, with data processing and analysis conducted using R language (Kappaetc package).

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Video analysis method

Video sources

This study selected official competition videos from the World DanceSport Federation (WDSF) and publicly available footage from international top-tier events such as the Blackpool Dance Festival as primary analysis materials.

Selection criteria

The videos were filtered based on the following conditions:

(1) High video resolution, enabling clear capture of dancers' joint angles, body posture, and weight transfer;
(2) Coverage of major Standard Dance styles (e.g., Waltz, Tango, Quickstep, Foxtrot, Viennese Waltz);
(3) Appropriate video duration, allowing complete demonstration of the initiation, intermediate, and concluding phases of technical movements.

Video observation and movement analysis

The videos were analysed frame-by-frame to meticulously document the performance characteristics of each technical movement. Qualitative analysis was conducted in conjunction with sports biomechanics principles to summarize the mechanical laws governing fundamental Standard Dance techniques.

Interdisciplinary research method

Drawing on relevant research findings from sports biomechanics, this study analyses the dynamic characteristics and mechanical key points of fundamental Standard Dance techniques based on Standard Dance technical theory and biomechanical principles, aiming to uncover the mechanical laws inherent in these techniques.

RESULTS

Selection of fundamental standard dance techniques

As a highly standardized dance form, Standard Dance comprises a technical system built upon various fundamental techniques. These techniques not only form the foundation of dance movements but also serve as the core support for dancers' expressiveness and competitive performance. The five Standard Dance styles—Waltz, Tango, Quickstep, Foxtrot, and Viennese Waltz—each possess distinct characteristics, with their technical movements adhering to specific biomechanical principles. Based on the classification of Standard Dance techniques by the World DanceSport Federation, the techniques are categorized into 12 elements: weight transfer, rise and fall, swing, contra body movement, inclination, rotation, shoulder leading, extension, heel turn, twist, heel pull, and pivot. These techniques collectively form the technical framework of Standard Dance, serving as the foundation for dancers to execute complex movements and demonstrate advanced dance skills.

Expert approval rate statistics

Table 1 presents the expert approval rates for each fundamental technique (calculated as the number of approvals divided by the total number of experts). Among these, the approval rates for rise and fall, weight transfer, contra body movement, swing, inclination and rotation are all 100%, indicating unanimous expert consensus that these techniques constitute the core foundation of Standard Dance. The approval rates for extension and shoulder leading are 80% and 70% respectively, while pivot, heel turn, twist, and heel pull each demonstrate 50% approval rates, indicating these techniques hold comparatively lesser importance in

the foundational framework of Standard Dance and reflecting discernible divergence among expert assessments.

Table 1. Expert approval rate statistics for fundamental Standard Dance techniques.

No.	Fundamental technique	Expert approval rate
1	Rise and Fall	100%
2	Weight Transfer	100%
3	Contra Body Movement	100%
4	Swing	100%
5	Inclination	100%
6	Rotation	100%
7	Extension	80%
8	Shoulder Leading	70%
9	Pivot	50%
10	Heel Turn	50%
11	Twist	50%
12	Heel Pull	50%

Gwet's AC1 coefficient analysis

To further evaluate the consistency of expert opinions on the recognition of fundamental Standard Dance techniques, Gwet's AC1 coefficient was employed for statistical analysis.

(1) Data organization

The evaluation results from each expert were recorded, and the total number of approvals for each technique was calculated.

(2) Calculation of observed agreement (*Pa*)

The observed agreement (*Pa*) represents the actual rate of agreement among experts, calculated using Formula (1).

$$P_a = \frac{a(a-1)+d(d-1)}{N(N-1)} \quad (1)$$

a is the number of experts approving the technique;
d is the number of experts disapproving the technique;
N is the total number of experts (*N* = *a*+*d*).

(3) Calculation of chance agreement (*Pe*)

The chance agreement (*Pe*) represents the rate of agreement among experts under random conditions, calculated using Formula (2).

$$P_e = \frac{1}{k-1}\sum p_c(1-p_c) \quad (2)$$

p_c is expert approval rate for technique *c* (number of approving experts / total number of experts) ;
k is the number of rating categories (2 categories: approved or not approved).

(4) Calculation of Gwet's AC1 coefficient

Gwet's AC1 coefficient is calculated using Formula (3).

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$$AC1 = \frac{Pa-Pe}{1-Pe} \quad (3)$$

The AC1 coefficient ranges from [−1,1], and its interpretation is as follows:
AC1 ≤0: Agreement is lower than chance;
0< AC1 ≤0.20: Slight agreement;
0.20< AC1 ≤0.40: Fair agreement;
0.40< AC1 ≤0.60: Moderate agreement;
0.60< AC1 ≤0.80: Substantial agreement;
AC1 >0.80: Almost perfect agreement.

(5) Result analysis
Based on the expert survey data, Gwet's AC1 coefficients were calculated for each technique, with the results presented in Table 2.

Table 2. Analysis of expert consensus on fundamental standard dance techniques.

Fundamental technique	Observed agreement (*Pa*)	Chance agreement (*Pe*)	Gwet's AC1 coefficient	Agreement level
Weight transfer	1.00	0.00	1.00	Almost perfect agreement
Rise and fall	1.00	0.00	1.00	Almost perfect agreement
Contra body movement	1.00	0.00	1.00	Almost perfect agreement
Swing	1.00	0.00	1.00	Almost perfect agreement
Inclination	1.00	0.00	1.00	Almost perfect agreement
Rotation	1.00	0.00	1.00	Almost perfect agreement
Extension	0.644	0.16	0.575	Moderate agreement
Shoulder leading	0.533	0.21	0.410	Moderate agreement
Pivot	0.444	0.25	0.259	Fair agreement
Heel turn	0.444	0.25	0.259	Fair agreement
Twist	0.444	0.25	0.259	Fair agreement
Heel pull	0.444	0.25	0.259	Fair agreement

By calculating Gwet's AC1 coefficients for the 12 fundamental techniques, the results indicate that the level of expert consensus ranges from 0.259 to 1.00. Among these, six techniques—weight transfer, rise and fall, contra body movement, swing, inclination, and rotation—all achieved Gwet's AC1 coefficients of 1.00, indicating the highest level of expert consensus. This demonstrates that these techniques hold a central position in Standard Dance and should form the core of foundational training. In contrast, heel pull, twist, heel turn, pivot, shoulder leading, and extension showed Gwet's AC1 coefficients between 0.259 and 0.575, reflecting relatively lower expert consensus. These techniques are considered less critical in foundational Standard Dance training compared to the aforementioned six techniques.

Expert survey results
Experts unanimously agree that fundamental techniques are the most characteristic and essential elements of Standard Dance, serving as the foundation for executing complex movements and demonstrating advanced dance skills. Among the 12 fundamental techniques, weight transfer, rise and fall, swing, inclination, contra body movement, and rotation are identified as the core of Standard Dance foundational training. Based on these findings, this study focuses on in-depth analysis and research of these six techniques.

Biomechanical principles of fundamental standard dance techniques

The "S"-shaped kinetic chain conduction sequence principle

Standard Dance is a coordinated and continuous full-body movement, characterized as a flowing dance style that exhibits various dynamic attributes driven by force. The source of force and its scientifically efficient application are fundamental to Standard Dance teaching and training. In swing-based dances (excluding Tango), the rise technique, particularly the upward movement, better demonstrates the dancer's control over music and expression through body language, thereby enhancing artistic expressiveness. The International Dance Teachers Association (IDTA) Dance Technique Book describes the rise and fall as follows: "*The rise is achieved by the lifting action of the leg muscles, straightening of the knees, and upward extension of the body, typically accompanied by the lifting or raising of the heels; the fall involves lowering from the toes to the heel of the supporting foot, followed by the relaxation of the knees in preparation for the next step*" (Horward, 1976).

The rise and fall technique involves the movement of multiple joints, including the ankle, knee, hip, torso, cervical spine, and head, as well as the activation of associated muscles. During movement, the body's joints form an "*S*"-shaped full-body coordinated kinetic chain (as shown in Figure 1), adhering to the principle of joint activation sequence. Energy is generated through the driving force of the lower limb's large muscle groups and transmitted upward layer by layer. Through the coordinated efforts of the torso and distal limb's small muscle groups, combined with lateral rotation and longitudinal spatial extension, the artistic presentation of the dance is achieved. Initially, the downward movement is generated by utilizing body gravity, causing the centre of gravity to lower. The bending of the ankle and knee joints forms an "*S*"-shaped posture, where the buffering force generated by energy storage counteracts the deformation force resulting from the stretching of leg muscles. Subsequently, the release of muscular elastic force and the contraction of thigh muscles drive the body's centre of gravity to rise from a low to a high position through knee extension. This is accompanied by the extension of the knee, ankle, and toes, transmitting energy upward through the body's joints. Ultimately, the energy reaches the torso and extends to the distal limbs and head, expanding into the surrounding space and creating an energy conduction curve (as shown in Figure 2), thereby producing a mesmerizing artistic effect in dance.

Figure 1. Chain transmission of joint forces during rise and fall.

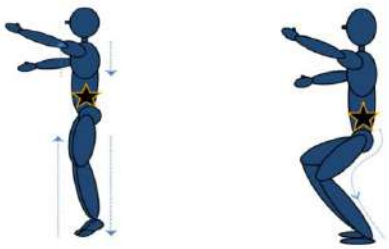

Figure 2. In-place rise and fall movement.

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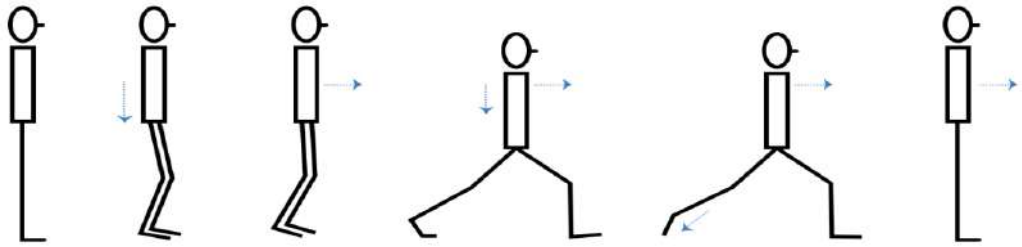
The principle of the "*S*"-shaped force conduction sequence is maximally utilized in the training of rise and fall techniques. These techniques are particularly crucial for beginners. Through descent practice, dancers can develop floor awareness, utilizing the gradual bending of the upper body, hip joints, knee joints, and ankle joints to create driving movements. By applying body gravity to the floor, a reactive force is generated, providing significant driving power. Ascent practice enables the coordinated and orderly transmission of force throughout the body, enhancing the dancer's stability and coordination.

Principle of central balance control in weight transfer

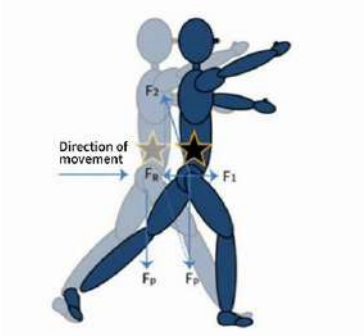
The technique of Standard Dance is essentially the technique of weight transfer. The fundamental skill of Standard Dance steps lies in the continuous shifting of the body's centre of gravity, making it the "*skill within skills*". The weight transfer in Standard Dance can be categorized into forward movement, backward movement, and side movement, each involving a continuous exchange and alteration of the weight-bearing points between the legs and feet. Weight transfer generally encompasses five movement phases: descent, resistance, control, propulsion, and recovery (as shown in Figure 3). Each phase requires dancers to possess a high level of dynamic balance maintenance ability, which is crucial for the fluidity and artistic expression of the dance.



Note. (a) Preparation; (b) Descent: Centre of gravity moves downward; (c) Resistance: Buffering and energy storage; (d) Control: Central balance position; (e) Propulsion: Rear foot propels to reach the front foot's centre of gravity position; (f) Recovery: Rising to the highest point.

Figure 3. Movement phases of weight transfer.

In the continuous flow of Standard Dance, weight transfer involves breaking the existing balance and establishing a new one. The tension generated by muscle contraction and the momentum of the body during movement must be controlled at specific positions to achieve stable balance. At this moment, the dancer's weight is F_P, the braking force of the driving leg is F_2, and the forward momentum is F_1. The resultant force F_R, formed by gravity and the braking force, is equal in magnitude and opposite in direction to the forward weight F_1, cancelling each other out. This creates a controllable balanced movement, referred to as "*central position balance*" (as shown in Figure 4). Taking forward movement as an example: The "*S*"-shaped bending of the body's joints during the buffering descent provides the driving force for movement. Before moving, the centre of gravity lowers to the ball of the supporting foot. When the driving foot reaches the maximum stride, the body's centre of gravity is positioned between the heel of the front foot and the ball of the rear foot, achieving "*central position balance*". As the front foot fully contacts the floor, the ball of the rear foot pushes naturally and smoothly, allowing the body's centre of gravity to transfer quickly and harmoniously to the front foot, followed by closing the feet and rising to recovery. This process occurs in the dynamic movement of each dance step, enabling the dance to continuously flow in balance.



Caption: The equilibrium condition is (F1+FR = 0). FP: Dancer's weight. F1: Forward momentum. F2: Braking force. FR: Resultant force of the balance system.

Figure 4. Force diagram of central position balance control.

Principle of conservation of angular momentum in contra body movement

During walking, the human body retains a contralateral movement pattern to maintain the stability of the torso and head relative to the body's longitudinal axis. The arms swing in opposition to the legs, forming a "*contra body movement*" (as shown in Figure 5). The swinging motion of the upper limbs helps counteract the rotational effect of the lower limbs' angular momentum during walking, adhering to the mechanical law of conservation of angular momentum: $M \cdot \Delta t = I\omega_2 - I\omega_1$. $M \cdot \Delta t$ represents the impulse moment, and $I\omega$ is the angular momentum of a rotating object, referred to as the moment of momentum. Standard Dance effectively applies this principle, termed "*contra body movement*".

Figure 5. Contra body movement.

Contra body movement refers to the motion where one leg moves forward or backward while the corresponding side of the body moves in the same direction. This dynamic is often used in the preparatory phase of turning or rotational movements in dance. In moving dance steps, taking a right turn as an example, when advancing or retreating, the movement of the stepping foot is accompanied by the rotation of the shoulder and hip on the opposite side of the body, creating a cross-power mechanism. The angular momentum generated by the contra body movement counteracts the angular momentum of the freely swinging lower limbs (as shown in Figure 6), maintaining a stable positional relationship between the wrist, elbow, shoulder, and hip joints on the partner's side. This not only ensures the stability of the partner's frame but also allows for an expansive and graceful posture during complex dance movements. In rotational movements, the contra body movement serves as an essential mechanical condition for turning. Before initiating a rotational step, the body moves in the opposite direction, generating a reactive force through the internal twisting of the body. This not only ensures the balance of the body's forward motion during the leading

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step but also provides the turning force for the rotation. By utilizing the contra technique, dancers achieve a flawless and fluid rotation.

(c) (b) (a)

Caption: Angular momentum conservation: $M \cdot \Delta t = I\omega_2 - I\omega_1$. M: Torque. Δt: Time interval. I: Moment of inertial. ω_1, ω_2: Initial and final angular velocities. (a) Preparation phase: Left hip forward, weight on the left foot, with the corresponding left shoulder slightly behind; (b) Twist phase: Right hip and left shoulder rotate toward each other, right leg swings forward, reaching the central balance position; (c) Final phase: The left foot pushes to generate driving force, acting on the left shoulder and the left side of the body, achieving the maximum amplitude of the contra body movement.

Figure 6. Phases of contra body movement during a standard dance right turn.

Principle of kinetic-potential energy conversion in swing

The term "*swing*" originates from physics, referring to the periodic pendulum motion of a freely moving object around a fixed point. Swing resembles the motion of "*swinging on a swing*", with its most fundamental dynamic characteristic being the mutual conversion of gravitational potential energy and kinetic energy. According to the law of conservation of energy, the total mechanical energy of an object remains constant during the swing process. This means that the mutual conversion between kinetic and potential energy adheres to the principle of energy conservation. Specifically, at the highest points of the swing (points A and B), the object possesses maximum potential energy and zero kinetic energy. At the lowest point (point C), the object has maximum kinetic energy and minimum potential energy. As the swing position rises, kinetic energy gradually converts into potential energy, and the speed decreases. Conversely, as the swing position lowers, potential energy converts into kinetic energy, and the speed increases (as shown in Figure 7). This periodic energy conversion is the core characteristic of swing motion.

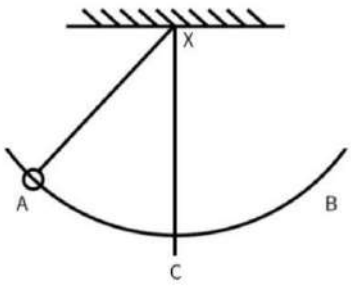

Figure 7. Principle of swing.

Swing is the fundamental movement mode of Standard Dance, characterized by the mutual conversion of kinetic energy and gravitational potential energy. The effective utilization of this energy conversion significantly enhances dancers' training efficiency and competitive performance. Waltz, Viennese Waltz,

Quickstep, and Foxtrot share the technical commonality of generating swing through gravitational potential energy, which is why these dance styles are collectively referred to as "*swing dances*" (Liu & Wu, 2012).

From a kinematic perspective, swing technique provides an efficient method of energy replenishment. Taking the Waltz sidestep as an example: the dancer begins at the highest point (point A) by relaxing the knees and lowering the centre of gravity through a knee-bending buffering motion, generating movement speed and lateral momentum. Simultaneously, the leg swings with the hip joint as the pivot point, reaching the central balance position at the lowest point (point C) and attaining maximum speed. The supporting leg then pushes, completing the rise of the centre of gravity through a swinging motion, converting kinetic energy into potential energy, and reaching the highest point (point B) (as shown in Figure 8). This cyclical process continuously generates the dynamic rhythm of dance swing. Throughout the entire process, the effects of gravity and motion inertia are fully utilized, creating a captivating dance rhythm that combines acceleration and control, movement and stillness. By understanding the principles of swing, dancers learn to better harness external forces and utilize motion inertia to complete dance movements in a passive manner. This approach makes the movements more effortless, lighter, and less fatiguing, enhancing the efficiency of the actions and allowing the dance to appear more relaxed, natural, and graceful.

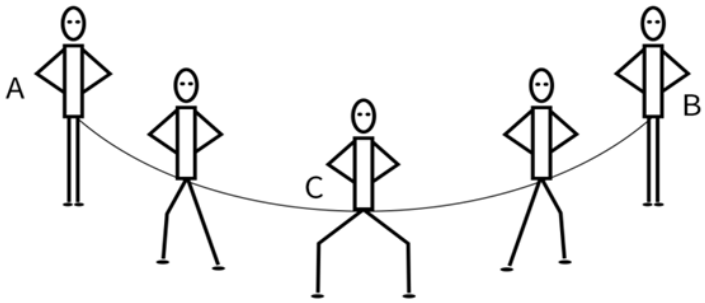

Figure 8. Schematic diagram of swing motion.

Maintaining balance in inclination – muscular torque

In Standard Dance, body inclination occurs during rise-and-fall and turning movements. Inclination is generated by swing, with swing being the cause and inclination the result. Inclination is a unique aesthetic feature of Standard Dance, a form of body line expression, and an essential component of dance technique and artistic expression.

Inclination is a dynamic posture, and maintaining this posture requires the coordinated involvement of muscles throughout the body, achieved through the regulation of different muscular torques to achieve balance. In dance, when the centre of gravity swings laterally to the opposite side, the vertical line of the centre of gravity in the sagittal plane tends to extend beyond the base of support due to motion inertia, leading to a loss of balance. To decelerate and maintain balance, it is necessary to create mechanical conditions that sustain balance on the toes. Through visual and proprioceptive feedback, the body generates internal muscular torques to counteract the motion, thereby maintaining posture and achieving a stable equilibrium. Thus, the inclination movements in Standard Dance align with the requirements of mechanical balance. Driven by the movement of the centre of gravity and through the swing, the centre of gravity remains above the pivot point of the single supporting foot. The pivot point and the ground generate a frictional force F_1. As the body's centre of gravity is braked during movement, the motion inertia acts in the opposite direction to the braking force. The gravitational force and the ground reaction force produce an elastic deformation force

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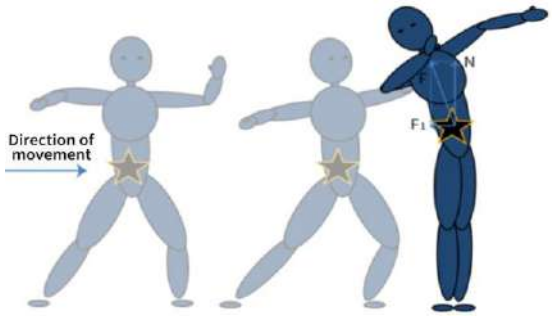
N. The combined effect of the frictional force and the elastic force results in a muscular pulling force *F*. On the side of the moving foot, muscle stretching creates an elongated and relaxed line, while on the opposite side, the latissimus dorsi contracts. Under the combined action of gravitational torque and muscular torque, the body's vertical axis tilts relative to the centre of gravity's vertical line, causing the vertical plane to rotate around the sagittal axis. This results in a stable upward and diagonal movement of the body's centre of gravity, showcasing the dancer's graceful body lines and posture (as shown in Figure 9).



Caption. N: Elastic Force. F1: Frictional Force. F: Muscular Pulling Force. (a) Central balance position; (b) Lateral foot centre of gravity position; (c) Inclination balance position.

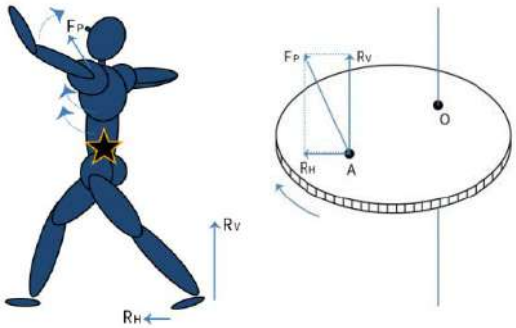
Figure 9. Formation of inclination balance through muscular torque in standard dance.

From a biomechanical perspective, tilting the centre of gravity causes the body's longitudinal axis to deviate from the vertical ground coordinate, counteracting centrifugal and forward momentum forces. This creates a dance posture where the chest, waist above the diaphragm, and head extend upward, aiding deceleration and maintaining a new state of balance. From a ballet aesthetic perspective, the characteristics of "*straightness, uprightness, and elongation*" are perfectly expressed. "*Straightness*" refers to the midsection of the body (typically the torso) maintaining a perpendicular alignment with the floor at all times. "*Uprightness*" involves lifting the hips and engaging the lower back, with the hip joints and midsection of the body tightened and pushed upward. "*Elongation*" emphasizes the upward lift of the diaphragm driven by the midsection, achieving both vertical lengthening of the entire body and horizontal extension of the frame. Particularly, the muscles on one side of the ribcage expand and stretch outward, generating muscular tension. This is accompanied by the dynamic opening of the chest and waist, creating a line that extends from the ankles, legs, and hip joints through the spine, chest, waist, and head, all the way to the hands and gaze, reaching upward and outward. This results in a beautifully artistic effect.

Transfer of angular momentum in rotational techniques

According to sports biomechanics, the rotational movements performed by the human body can generally be divided into two major categories: rotational movements of the body in a supported state and rotational movements in an unsupported (aerial) state (Sports Biomechanics Writing Group, 2019). In Standard Dance, rotation is an action that revolves around the vertical axis of the body with the foot as the pivot point. It is also a type of rotation performed while moving. Based on the angle of rotation and the amount of movement in the steps, it can be categorized into three types: pivot, spin, and natural turn (ADTV German Dance Teachers Association, 2014). Rotation is a core technique in Standard Dance, adhering to the mechanical principles of human body rotation. Whether it is a natural turn or a pivot, there must be an application of angular momentum relative to the axis of rotation (as shown in Figure 10). During the push-off phase of the leading step (left foot), the dancer is subjected to a vertical component force R_V and a horizontal component force

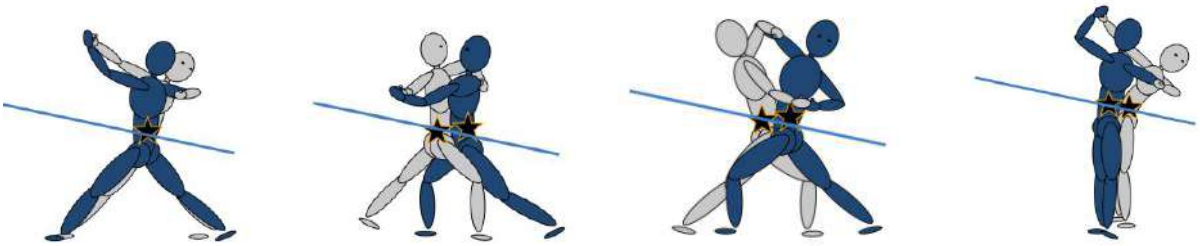
R_H, which combine to form a resultant force F_P acting on the same-side shoulder and torso of the dancer. The centre of gravity of the body shifts to the side of the resultant force's point of application, generating rotation in the horizontal plane around the supporting leg (right foot) as the axis.



Caption. RV: Vertical component force. RH: Horizontal component force. FP: Resultant force. O: Centre of gravity pivot point. A: Eccentric force pivot point.

Figure 10. The role of eccentric force in the contra body movement of Standard Dance.

The complete rotational technique in Standard Dance is typically broken down into three phases: the "*Contra Body Movement*" phase, the "*Rotation*" phase, and the "*Conclusion*" phase (as shown in Figure 11). Using a forward or backward step as the reverse lead, the dancer generates coordinated movement of the upper and lower limbs through the push-off of the supporting foot against the floor and the twisting of internal body forces. Subsequently, the moving foot lands and cushions, creating a braking effect. Due to the presence of motion inertia, the opposite side of the body retains its movement speed during braking. The rotation of the upper body forms an eccentric braking force, which generates angular momentum. This angular momentum is transferred within the body, driving the lower body to rotate around the pivot point of the braking foot and the vertical axis of the body's centre of gravity. Due to the generation of rotational inertia during the rotation phase, after the completion of the rotational movement, the dancer regulates the stretching and contraction of the muscles across various joints through internal bodily forces, demonstrating infinite spatial extensibility and dance tension.



Note. (a) Preparation phase: Left foot moves forward; (b) Contra body movement phase: eccentric braking generates angular momentum, body rotates 1/4 to the right; (c) Rotation phase: Momentum transfer, utilizing muscle tension to complete an additional 1/8 right turn of the body; (d) Conclusion phase: Supporting leg pushes, body rises and swings, extending with inclination.

Figure 11. Transfer of angular momentum in the contra body movement of a right turn in Standard Dance.

Rotation technique is one of the core skills that Standard Dance dancers must master. It is widely applied in the movement combinations of various dance styles, not only serving to connect movements but also enhancing the aesthetic appeal of the dance through smooth rotations, fully showcasing the dancer's physical

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control and artistic expression. To improve the effectiveness of rotations, dancers can optimize their performance through the following approaches:

(1) Maximize the utilization of muscular strength to generate greater driving force:
The existence of torque is a prerequisite for body rotation. According to the torque formula $M = F \cdot r \cdot \sin\theta$, it is evident that during the contra body movement, the conservation of momentum between the upper and lower limbs plays a crucial role. The greater the muscular torque generated by the body, the higher the angular velocity produced during rotation. The magnitude of muscular torque depends on both the strength of the muscles and the length of the muscle arm. Therefore, to enhance rotational power in dance, dancers need to engage in training that increases muscle strength and expands the range of motion of the body.

(2) Adopting appropriate body movements to reduce the moment of inertia and achieve greater angular acceleration:
According to the principles of mechanics, the angular acceleration of a rigid body's rotation depends on the torque and the moment of inertia, as expressed by the formula: $\beta = M/J$. In Standard Dance routines, to achieve greater rotational speed and optimal spinning performance, dancers can increase their rotational speed by reducing the moment of inertia while maintaining a constant muscular torque. For instance, during spinning training, both the male and female dancers are required to tighten their bodies, maintain a fixed partnership frame, and keep their body posture stable while rotating around a common axis. During pivot turns, dancers should keep their bodies compact, engage the inner muscles of both legs, and control the working leg to stay close to the supporting leg, thereby reducing the rotational radius and achieving greater angular velocity.

DISCUSSION

This study, grounded in the theoretical framework of sports biomechanics, systematically investigates the mechanical principles underlying fundamental Standard Dance techniques and their application in dance movements. The research focuses on elucidating the mechanical characteristics of Standard Dance techniques through biomechanical principles, while also uncovering the mechanisms through which these characteristics influence dancers' performance. Through a comprehensive analysis of techniques such as rise and fall, weight transfer, contra body movement, swing, sway, and rotation, the study further reveals the biomechanical laws governing Standard Dance movements. Specifically, the findings indicate that the "*S*"-shaped kinetic chain transmission sequence in the rise and fall technique optimizes energy transfer efficiency, the dynamic balance control mechanism in weight transfer enhances dancers' postural stability, the conservation of angular momentum in contra body movement establishes a biomechanical foundation for rotational dynamics, the conversion between potential and kinetic energy in swing technique amplifies dance fluidity and artistic expressiveness, the regulation of muscular torque in sway technique sustains dynamic equilibrium, and the transfer of angular momentum in rotation technique provides mechanical support for the execution of complex axial rotations.

In contrast to existing studies that predominantly focus on the biomechanical relationships of partner interaction in Standard Dance or technical differences across dance styles, this study systematically deconstructs the mechanical pathways of individual fundamental techniques in Standard Dance. It provides an in-depth analysis of key issues such as energy transfer efficiency and movement economy, offering new theoretical foundations for the refinement of Standard Dance technical training. Standard Dance practitioners rely more heavily on the coordinated movement of the hip, knee, and ankle (Yoshida et al., 2022), a finding that aligns with this study's conclusion that weight transfer requires multi-joint coordinated control. However,

their research primarily focused on technical differences across dance styles and did not delve deeply into the universal fundamental techniques of Standard Dance. Chang et al. (Chang et al., 2019), in their research, emphasized the central role of biomechanics in optimizing dance movements and proposed that "*joint coordination directly influences movement fluidity*", which resonates with the "*S-shaped kinetic chain transmission sequence*" theory proposed in this study. Nevertheless, Chang's research remained largely theoretical and did not analyse the mechanical pathways of specific technical movements in depth. Wu et al. (Wu et al., 2023) supported the view in this study that "*weight transfer requires dynamic balance control*", but their research mainly analysed the mechanical characteristics of partner interaction, whereas this study places greater emphasis on the systematic interpretation of the biomechanical principles of individual techniques. Chang et al. (Chang et al., 2019) and this study both revealed the central role of joint coordination in movement stability and economy, but this study further explains how coordination is achieved through mechanical pathways, providing more specific theoretical tools for technical training.

However, this study still has certain limitations. For instance, it does not delve deeply into the individual differences among dancers, such as age, gender, training experience, and body morphology. Additionally, the research focuses on a general framework of Standard Dance techniques and does not systematically compare the differences in mechanical mechanisms across different dance styles, such as Waltz, Tango, and Quickstep. Furthermore, the biomechanical mechanisms of partner interaction in Standard Dance remain an area for further exploration.

CONCLUSION

Based on expert surveys, literature analysis, and statistical methods, the research identified six core techniques of Standard Dance (weight transfer, rise and fall, swing, contra body movement, sway, and rotation) as research subjects and systematically explored their biomechanical principles and applications in dance movements. The research found that the "*S*"-shaped kinetic chain transmission sequence in the rise and fall technique optimizes energy transfer efficiency, the dynamic balance control mechanism in weight transfer enhances dancers' stability, the conservation of angular momentum in contra body movement provides a mechanical foundation for rotational actions, the regulation of muscle torque in sway technique maintains dynamic balance, the conversion between potential and kinetic energy in swing technique enhances the fluidity and artistic expression of dance, and the transfer of angular momentum in rotation technique provides mechanical support for the execution of complex rotational movements. These findings offer new biomechanical theoretical foundations for Standard Dance technical training.

The research addresses the gap in existing literature regarding the biomechanical analysis of fundamental techniques in Standard Dance. Although previous studies have explored joint coordination and dynamic balance in dance, research on the mechanical characteristics and synergistic effects of Standard Dance techniques remains limited. The research provides new perspectives and contributions for Standard Dance training research, and its outcomes will help dancers more efficiently improve their technical skills and artistic expression, further promoting the scientific and systematic development of Standard Dance training.

The research adopted an interdisciplinary research approach, combining sports biomechanics theory and video analysis methods to conduct a comprehensive biomechanical analysis of Standard Dance techniques, laying a scientific theoretical foundation for the innovation of training content and methods in Standard Dance. Future research can further expand on this basis by incorporating motion capture technology, electromyography, and energy metabolism testing to achieve more precise quantitative analysis of the mechanical characteristics of Standard Dance techniques. Additionally, in-depth exploration of the impact of

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individual differences among dancers on technical movements, as well as the biomechanical mechanisms of different dance styles and fundamental techniques in partner interaction, will contribute to a deeper understanding of the movement principles of Standard Dance and further advance the scientific development of International Standard Dance training.

AUTHOR CONTRIBUTIONS

Conceptualization, TW and PF; methodology, TW; software, PF; formal analysis, PF; investigation, TW; resources, TW; data curation, PF; writing—original draft preparation, TW; writing—review and editing, PF; visualization, TW and PF; project administration, TW and PF. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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ORIGINAL ARTICLE

Judo as a didactic tool for emotional growth: Anger management and positive youth relationships

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ABSTRACT

Combat sports such as judo offer a unique opportunity to develop emotional and social skills. This study investigates how the practice of judo influences anger management and promotes positive interpersonal relationships. A mixed methods approach combining qualitative and quantitative methods was used to explore subjective experiences and measure participants' emotional and interpersonal skills. The sample consisted of 60 judo practitioners and a control group of 60 non-practitioners, all students at a secondary school in Caserta, aged between 10 and 13. Data were collected using the Angry Cognition Scale-Revised and The Interpersonal Relations Test (TRI), supplemented by semi-structured interviews. The results show that judo not only helps to regulate emotions such as anger but also improves the ability to form positive relationships.

Keywords: Combat sports, Emotional intelligence, Anger, Interpersonal skills.

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INTRODUCTION

Emotional management and the ability to build positive relationships are fundamental aspects of psychological and social well-being. Martial arts, particularly judo, are based on principles that promote emotional control, self-discipline and respect for others.

Emotional intelligence, defined by Goleman (1995) as the ability to identify, understand and manage one's own and others' emotions, plays a crucial role in the development of interpersonal skills and emotional regulation. According to Mayer and Salovey (1997), emotional intelligence has four main dimensions: awareness, use, understanding and management of emotions. These dimensions are closely related to the ability to cope with stressful situations, resolve interpersonal conflicts and promote individual well-being (Brackett et al., 2011).

In addition, several studies have shown that anger regulation is one of the most difficult emotional skills to develop, but also one of the most important for the quality of interpersonal relationships. Averill (1982) emphasised that anger is not only a negative emotional response, but also a signal that can facilitate the resolution of social problems if properly managed. However, if poorly regulated, it can lead to impulsive behaviour and conflict (Deffenbacher et al., 1996). Martial arts provide a unique context in which emotional regulation strategies can be learned in a practical and experiential way. Judo in particular, with its principles of mutual respect, self-control and fair play, helps to create an environment in which it is possible to learn to manage intense emotions such as anger. Gardner and Moore (2006) showed that physical activity combined with learning specific skills related to emotional awareness can improve anger management and promote greater emotional resilience. Recent studies on emotional intelligence in sport have highlighted how regular practice of disciplines such as judo is associated with reduced levels of aggression and increased empathy and cooperation among peers (Zahra et al., 2014). Furthermore, the work of Hatzigeorgiadis et al (2008) has shown that structured sport promotes the development of skills such as self-control, emotional regulation and interpersonal conflict management, which are fundamental aspects of social well-being. Another important contribution comes from Lochbaum et al. (2016), who found a link between sport practice and the development of emotional self-efficacy, i.e. the belief that one can successfully regulate one's emotions even in high-pressure situations. Furthermore, according to Laborde et al. (2016), regular sports practice contributes to the improvement of stress management skills, fostering greater emotional resilience and a better quality of social relationships. Further insights are provided by Petrides et al. (2004), who highlight that emotional intelligence is a significant predictor of prosocial behaviour and success in interpersonal relationships, aspects that find fertile ground in sport. Finally, Chan et al. (2012) highlighted how structured physical activity promotes not only physical health, but also psychological well-being by improving emotional awareness and control.

The aim of this study is to analyse how judo, practised by students aged between 10 and 13 in a school in Caserta, contributes to anger management and the building of positive relationships. To this end, validated psychometric instruments such as the Angry Cognition Scale-Revised (ACS-R), to assess anger-related thoughts, and the Interpersonal Relations Test (TRI), to measure the quality of social interactions, will be used. In addition, semi-structured interviews with participants will enrich the understanding of the mechanisms linking judo practice to these aspects.

Aim of the study

The main aim of this study was to investigate how the practice of judo can influence anger management skills and improve interpersonal relationships in boys between the ages of 10 and 13. Specifically, the study

investigated whether the integration of judo techniques, based on principles of respect and self-control, could be an effective means of developing emotional and interpersonal skills, and compared the results with those of boys participating in traditional physical education sessions.

MATERIALS AND METHODS

The study adopted a mixed approach, integrating quantitative and qualitative methods to gain an in-depth understanding of the emotional and relational dynamics involved.

Quantitative data were collected using validated psychometric instruments:

- Angry Cognition Scale-Revised (ACS-R): used to measure anger-related thoughts, assessing aspects such as frequency, intensity and management of angry thoughts.
- Interpersonal Relations Test (TRI): used to assess the quality of social interactions, measuring skills such as empathy, cooperation and assertiveness.

With regard to the analysis of qualitative data, semi-structured interviews were conducted to explore the subjective experiences of the participants, giving voice to their personal perceptions and reflections. In addition, direct observation during training sessions allowed for the analysis of relational dynamics and emotional management strategies applied in real-life contexts.

Participants

The study sample consisted of 120 students aged between 10 and 13 years attending a secondary school in Caserta. The sample was divided in two groups:

- Experimental group: 60 boys practising judo, with at least 2 years of experience and a minimum frequency of 2 training sessions per week.
- Control group: 60 boys not involved in martial arts or disciplines that emphasise emotional control, such as yoga or meditation.

Within each group, approximately 15% of the participants (9 students per group) were diagnosed with Attention Deficit Hyperactivity Disorder (ADHD). This was verified through clinical documentation provided by the families, which ensured an accurate assessment of the participants' condition.

Participation criteria

Children who met the following criteria were included in the trial:

- Aged between 10 and 13 years.
- Attending the middle school where the study took place.
- For the experimental group: active practice of judo for at least 2 years.
- For both groups: clinically documented diagnosis of attention deficit hyperactivity disorder (ADHD).
- Absence of serious physical or mental illnesses that could interfere with participation in the activities or use of the assessment instruments.

The inclusion of students with ADHD in both groups allowed us to investigate the impact of judo training on emotion management and interpersonal skills in a sample with particular difficulties in self-regulation and attention.

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Recruitment and informed consent

Participants were selected with the support of the school and families, with due regard for ethical principles and data confidentiality. Informed consent was obtained from parents or guardians, who agreed to the children's participation in both the sports activities and the data collection procedures.

Educational Intervention

The programme ran for 12 weeks and included fortnightly sessions integrated into the regular school curriculum. Each session lasted 90 minutes and took place during school hours, with the aim of promoting the physical as well as the emotional and relational development of the pupils.

The activities were designed on the basis of research showing that structured physical activity can promote not only the improvement of motor skills, but also the development of social and emotional skills (Bailey et al., 2013). In addition, the approaches used aimed to create a safe and supportive environment in which students could learn the value of mutual respect and emotional regulation (Holt et al., 2012).

Experimental group (judo practitioners)

The sessions for the experimental group were structured to integrate judo practice with activities aimed at emotional regulation and improving interpersonal skills.

1. Warm-up and physical preparation (15 minutes):Joint mobility exercises, stretching and playful activities were aimed at preventing injuries and improving concentration. The decision to include team games in the warm-up was motivated by the intention to promote group cohesion, a fundamental element in creating a positive and collaborative climate (Carron et al., 2005). These games stimulated a sense of belonging and broke down any relational barriers between participants, creating an environment conducive to learning (Côté et al., 2007).
2. Judo Techniques (45 minutes): The core phase of the training focused on learning basic judo techniques such as joint locks, projections, immobilisations and safe falls. These activities not only developed physical skills but also helped the children to understand the importance of physical control as a prerequisite for emotional control (Gardner & Moore, 2006). Simulated fighting exercises (randori) were supervised to avoid situations of excessive competitiveness and to emphasise the principles of self-control and cooperation that are fundamental to judo (Matsumoto, 2009). During the breaks, the coaches discussed the emotions experienced with the students, emphasising the link between body awareness and emotional management.
3. Emotional regulation activities (20 minutes): The practice of relaxation and mindfulness techniques, such as controlled breathing and visualisation, was based on evidence that these strategies can help children manage intense emotions such as anger (Felver et al., 2016). Facilitated discussions allowed participants to reflect on emotions experienced during the training and share personal experiences, promoting empathy and emotional awareness (Brackett et al., 2011). Role-playing and brainstorming activities were used to simulate real-life situations, encouraging practical application of the emotional and relational skills acquired.
4. Debriefing and closing (10 minutes): The session ended with a time of sharing where the students could express their opinions about the activity. The coaches encouraged the students to think about how they could use what they had learned in judo to deal with situations of conflict or tension in everyday life, thus promoting a proactive approach to emotional management.

Control group (traditional physical education)

The control group took part in traditional physical education sessions, also 90 minutes long and held every two weeks. The activities focused on improving motor skills and physical well-being but did not include specific interventions related to emotional regulation or judo practice.

1. Warm-up and general motor activity (20 minutes): Stretching exercises, light running and motor games were designed to improve coordination and physical endurance. These activities were designed to prepare the body for intense physical activity while encouraging student participation (Caspersen et al., 1985).
2. Team sports (40 minutes): Football, volleyball or basketball games were designed to promote socialisation and teamwork. However, the focus remained on physical performance without addressing emotional or relational aspects (Eime et al., 2013).
3. Individual activities (20 minutes): Circuit exercises or muscle strengthening activities were designed to develop strength, agility and endurance. These exercises followed a traditional approach and were limited to improving physical skills without including emotional reflection (Dishman et al., 2004).
4. Debriefing (10 minutes): At the end of the session, students briefly discussed their level of enjoyment, but no emotional or relational aspects were explored.

Quantitative data analysis

Quantitative data analysis was carried out on the results of the two questionnaires administered to both the experimental and control groups, both before and after the intervention. The results of the Angry Cognition Scale-Revised (ACS-R) and the Test of Relationships (TRI) were compared to assess any changes in anger management and quality of interpersonal relationships. In addition, the results were analysed separately for the children with Attention Deficit Hyperactivity Disorder (ADHD) to see how the intervention might affect them specifically.

Angry Cognition Scale-Revised (ACS-R)

In the experimental group, mean scores related to angry thoughts decreased significantly from pre- to postintervention. Specifically, the frequency of angry thoughts decreased by 30% ($p < .01$), while the intensity of thoughts decreased by 25% ($p < .01$). These results indicate a significant improvement in self-control and anger management skills. In contrast, the control group showed no significant change, with less than a 5% change in total scores, suggesting that the traditional PE activities did not have a significant impact on anger management.

In particular, the reduction in the frequency of angry thoughts was even more pronounced for the children with ADHD in the experimental group, reaching 35%, whereas no significant improvement was observed for the children with ADHD in the control group (only a 3% reduction in angry thoughts). This finding highlights the effectiveness of the intervention in helping children with difficulties in emotional management, such as those typical of ADHD.

Test of Interpersonal Relationships (TRI)

In terms of the quality of interpersonal relationships, the experimental group experienced a significant increase in mean post-intervention scores on all dimensions measured. Empathy increased by 28% ($p < .01$), cooperation by 22% ($p < .01$) and conflict resolution skills by 26% ($p < .01$). These improvements highlight the effectiveness of judo training in improving interpersonal skills and fostering a more collaborative and respectful environment. In contrast, improvements in the control group were more limited, with an average

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increase of 10% in the socialisation dimension, mainly due to the group dynamics of team sports activities, but with no real progress in other areas such as empathy or conflict resolution skills.

For the boys with ADHD in the experimental group, the improvements were even more pronounced, with a 32% increase in empathy and a 30% increase in cooperation. These results suggest that the integrated approach of judo and emotional regulation had a particularly positive effect on boys with difficulties in social interactions, such as those associated with ADHD. In contrast, the scores of the boys with ADHD in the control group remained stable, with a marginal improvement of 5% in empathy and 7% in conflict resolution skills, and no apparent changes in the other relational dimensions.

Qualitative data analysis

Analysis of the qualitative data from the semi-structured interviews conducted with both teachers and pupils in the experimental and control groups provided an in-depth understanding of the participants' lived experiences and the relational and emotional dynamics that emerged during the programme. The interviews revealed significant differences in perceptions of the effectiveness of the proposed activities in the two groups, with a particular focus on children with Attention Deficit Hyperactivity Disorder (ADHD).

RESULTS

Opinions of the students in the experimental group

Pupils in the experimental group who took part in the judo sessions showed a high level of awareness of the emotional aspects of self-control and mutual respect. Many of the students expressed how judo helped them to 'feel calmer' and 'manage anger better'. One pupil commented: 'I used to get angry easily, but now I can stop and think before I act'. Another added: 'Judo has taught me never to hurt others and that makes me feel more in control of myself. This kind of reflection suggests that the integration of physical activity and emotional regulation had a positive impact on anger management and the growth of interpersonal skills. Another student pointed out: 'When we play group games, I can focus more on how I feel and not just on winning. This suggests that the group dynamics of judo, which emphasise cooperation and self-control, also had a positive effect on the quality of social interactions. In addition, some students reported that judo made them more 'aware' of their emotions: 'In judo, when I feel angry, the coach makes us stop and think and that helps me to understand what I am feeling'. This aspect of self-reflection was particularly valued as a tool for emotional growth.

Opinions of students in the control group

Pupils in the control group, who participated in traditional physical education sessions, showed a less pronounced perception of improved emotional competence. Although they enjoyed the team sports, the opinions collected did not suggest that the activities had a significant impact on emotion management. One boy said: 'I like playing football, but I don't think it helps me to calm down when I'm angry'. Another said: 'We never talk about how we feel, we just think about winning'. Another pupil added: 'Even though I play basketball with my friends, I still get frustrated when things don't go my way and there's no one to help me understand why I feel that way'. These responses suggest that although traditional physical activities promote socialisation and teamwork, there are no significant improvements in emotional regulation or interpersonal skills. Furthermore, some pupils revealed that they felt stressed by the competitiveness of team sports, with no real space to reflect on their feelings: 'In football, everything is a race and no one ever stops to talk about their problems'.

Teachers' opinions

The teachers who supervised both groups emphasised the importance of the integrated approach in the experimental group, pointing out that the inclusion of emotional regulation activities improved pupils' behaviour and participation. One teacher noted: The judo students seem more focused and respectful, not only in their physical activities but also in the way they interact with each other. Another added: 'Even when conflicts arise, I see that with judo the boys try to resolve them in a more peaceful and mature way'. Another teacher observed a significant change in the boys' ability to resolve conflicts among themselves: 'I have noticed that the boys who practise judo discuss more calmly and respectfully, whereas before they tended to react more impulsively'. With regard to the control group, teachers recognised that some pupils, although involved in group activities, tended to focus solely on the competitive aspect or physical performance, without deep emotional reflection. One teacher reported: In team games, the children are more focused on the end result rather than the social dynamics, and this creates difficulties in moments of conflict.

Specific views of boys with ADHD

The boys with ADHD in the experimental group were particularly positive about emotional regulation. One boy with ADHD said: 'When I was angry I couldn't stop, but now it helps me to think about my breathing and how I feel'. Another explained: 'In judo, when I get angry at someone, the teacher helps me to talk and understand why I am angry'. These reflections suggest that the boys with ADHD benefited significantly from the integrated approach of judo and emotional regulation, managing their anger better and improving their ability to resolve conflicts. One boy with ADHD added: 'It used to make me very angry that others did not understand how I felt, now with judo I try to explain better how I feel'. In contrast, boys with ADHD in the control group reported difficulties in maintaining concentration and managing emotions in competitive contexts. One of them said: 'Sometimes I feel like there's no room to calm down during football games, it's all too fast and chaotic'. This finding suggests that boys with ADHD may benefit more from programmes that combine physical activity with moments of emotional reflection. Another boy with ADHD remarked: When we're all focused on the game, it's hard to stay calm and think about my feelings.

In conclusion, the opinions gathered during the qualitative interviews reinforced the quantitative results, indicating that the integration of Judo and emotional regulation techniques had a positive impact on anger management and interpersonal skills, particularly for students with ADHD. Students in the experimental group perceived an increase in their emotional and interpersonal skills, whereas students in the control group did not show similar improvements. Pupils' and teachers' perceptions confirm that the holistic approach of judo, which integrates physical movement and emotional awareness, is particularly effective in promoting healthy emotional management and improving the quality of social interactions.

In-depth study of qualitative analysis topics

The interviews conducted with teachers and pupils in the experimental and control groups revealed a number of recurring themes relating to emotion management, behaviour regulation and the quality of social interactions. These themes provided an important insight into the differences between the two groups and the effectiveness of the integrated judo approach compared to the traditional approach of physical education alone.

Themes from the interviews with pupils in the experimental group

A central theme in the interviews with students in the experimental group was the importance of emotional awareness. Students reported how judo helped them to recognise and manage their emotions, particularly anger. This concept of emotional awareness proved crucial in the context of sport, where self-control and mutual respect are key aspects (Goleman, 1995). Internal reflection, as indicated by the students, was also

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stimulated by the active involvement of the coaches, who encouraged them to stop and think before reacting in conflict situations (Brackett et al., 2011). Many students also highlighted the aspect of cooperation in group games, where they not only learned to work together, but also to understand themselves and others better, fostering an environment of support and emotional growth (Zahra et al., 2014).

Another theme that emerged was conflict management. Students noted that judo provided them with tools to handle disagreements with peers in a more peaceful and mature manner, with an overall improvement in interpersonal relationships (Moore & Gardner, 2006). The ability to resolve conflicts in a more peaceful and reflective manner was seen as an aspect that positively influenced social dynamics outside of the sport. By emphasising self-control and respect for others, the practice of judo strengthened social skills that are fundamental to improving relationships with peers (Felver et al., 2016).

Themes from the control group interviews

In the control group, who participated in traditional physical education sessions, the issues raised were mainly related to competitiveness and a focus on the physical aspect of play rather than on emotions or behavioural regulation. Students pointed out that traditional physical activities such as football and basketball, while promoting socialisation and integration, did not create opportunities to reflect on their emotions (Eime et al., 2013). Competitiveness was seen as an element that sometimes exacerbated stress and frustration, without adequate space to manage these emotional states. Many children said that there was never a moment to talk about their feelings, only the importance of winning or improving physical performance (Zeidner et al., 2004).

Some students also reported feeling overwhelmed by the rush of the game, particularly in sports such as football, where the speed and intensity of the game made it difficult to focus on emotions. This confirms the importance of integrating physical activities with moments of emotional reflection, as evidenced by the research of Hatzigeorgiadis et al. (2008), which highlights the benefits of emotional awareness in improving the regulation of impulsive behaviour. The lack of a structured space for inner reflection may have prevented the children in the control group from developing the emotional skills necessary for healthy emotional management, particularly in times of conflict.

Themes from the teacher interviews

Teachers identified another important theme in the interviews: the difference in pupils' participation and behaviour during the activities. In the experimental group, teachers noticed an improvement in concentration and mutual respect, not only during physical training, but also in daily interactions between students (Theeboom et al., 2009). The integrated judo approach provided students with tools to deal with conflict situations in a more constructive and less impulsive way. This had a positive impact on the overall behaviour of the students, who were calmer and more willing to cooperate (Lochbaum et al., 2016). In particular, the boys who practised judo showed a more mature approach to conflict, seeking peaceful solutions rather than reacting impulsively as in the past (Moore & Gardner, 2006).

As for the control group, teachers acknowledged the good participation of pupils in group activities but noted that the prevailing competitive approach did not encourage deep reflection on emotional and relational dynamics. Although there was some socialisation, the boys tended to focus mainly on performance and the end result (Goleman, 1995) without developing adequate emotional awareness.

DISCUSSION

The results of this study suggest that integrating judo practice with activities aimed at emotional regulation and improving relational skills had positive effects on anger management and interpersonal dynamics in children aged 10 and 13. In particular, the experimental group that participated in the judo programme showed significant improvements in anger-related thought management and relational skills such as empathy, cooperation and conflict resolution. These findings were corroborated by qualitative interviews, which revealed increased emotional awareness and more mature conflict management among participants in the experimental group.

In line with the study's assumptions, quantitative data showed that boys in the experimental group, particularly those with ADHD, achieved significant improvements in rabies control compared to the control group. This finding is particularly relevant given that boys with ADHD often have significant difficulties in regulating emotions and managing social interactions. Judo, with its focus on mutual respect, self-control and body awareness, appears to provide an ideal context for developing emotional and relational skills that go beyond mere physical performance (Moore & Gardner, 2006). Improvements in the quality of interpersonal relationships in the experimental group were also confirmed by increased scores on empathy, cooperation and conflict resolution dimensions. This underlines the value of structured sports activities not only for physical improvement, but also for the development of emotional awareness (Goleman, 1995).

The findings suggest that judo can provide a safe environment in which boys learn to interact respectfully by putting into practice the skills they acquire in training, and that these skills are also reflected in everyday life. Research by Zahra et al (2014) supports this claim, highlighting how the practice of martial arts can improve self-control and foster positive relationships between participants. The technicians' focus on listening to emotions during and after training played a crucial role in fostering emotional awareness, which in turn contributed to more effective management of emotions and improved relationships with peers (Brackett et al., 2011). In contrast, the control group, who participated in traditional physical education sessions, did not show the same progress. Although the group activities promoted socialisation and cooperation, they did not incorporate structured emotional regulation interventions, which limited the effectiveness of the programme in addressing issues such as anger management and conflict resolution. This finding is consistent with the literature, which suggests that traditional physical activity, while useful for physical well-being, is not sufficient to systematically develop emotional and relational skills (Eime et al., 2013).

The fact that the control group, and particularly the children with ADHD, did not benefit significantly from traditional activities highlights the importance of holistic approaches that combine physical movement with emotional reflection. In particular, children with ADHD have shown greater difficulty in maintaining concentration and coping with conflict situations when specific spaces for emotional reflection were not provided (Hatzigeorgiadis et al., 2008). This highlights the need for personalised interventions for these children that are able to integrate physical activity with moments of emotional awareness, as demonstrated by the experimental group (Felver et al., 2016). Pupil and teacher feedback further corroborated the quantitative results, showing that the boys in the experimental group not only improved their emotional management, but also developed a greater awareness of themselves and others. Reflecting on their emotional states, as suggested during the judo sessions, allowed them to approach conflict situations in a more mature way, reducing the tendency to react impulsively (Zeidner et al., 2004). Finally, qualitative observations highlighted another key aspect: the importance of the relationship between the coach and the participants. Boys in the experimental group reported that the instructor's guidance, which stimulated moments of emotional reflection during training, was fundamental in promoting the conscious management

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of anger and conflicting emotions (Lochbaum et al., 2016). This point highlights the importance of a pedagogical approach that is not limited to teaching physical techniques, but also includes the emotional aspect, which is often overlooked in other forms of physical activity (Theeboom et al., 2009).

CONCLUSION

The study highlighted the effectiveness of judo as a tool for improving anger management and interpersonal skills in boys aged 10-13, with a particular impact on young people with ADHD. The integrated approach, which combines sports practice with emotional awareness activities, was found to be more effective than traditional physical activities in developing socio-emotional and interpersonal skills. This approach highlights the importance of educational programmes that combine physical exercise and emotional regulation and provides a versatile and adaptable intervention model.

These findings provide a solid basis for further research and interventions to improve children's emotional and relational well-being in both school and social settings. The introduction of such programmes could have a long-term positive impact, helping to create a generation of young people who are more aware, resilient and able to face the challenges of everyday life with greater emotional balance and relationship skills.

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The writing of this paper was a joint effort by all authors.

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ORIGINAL ARTICLE

Mental Strength Scale (MSS-9): Factor structure and reliability

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ABSTRACT

Mental strength represents a person's ability to persist through obstacles and recover from failures. The Mental Strength Scale was first developed as a simple tool for field applications for coaches and mental performance practitioners to determine strategic plans to improve a person's mental strength. Study 1 aimed to assess, via confirmatory factor analysis, the Mental Strength Scale factor structure in a sample of Brazilian jiu-jitsu and judo athletes. Sample 1 included 630 combat sports practitioners (79.7 % males), representing 420 Brazilian jiu-jitsu and 210 judo participants from 18 to 60 years of age. Results indicated that the hypothesized factor structure was not a good fit for the data. As a result, Study 2 was conducted to propose modifications to the scale and reassess its structure via exploratory factor analysis in a sample of the general population. Sample 2 included 316 representatives of the United States general population (68% male) from 21 to 60 years of age. Based on the EFA, a one-factor solution is championed, with nine items retained (Appendix A). Cronbach's alpha of .81 was computed for the retained items, indicating good internal consistency and reliability. Future studies are encouraged to conduct follow-up confirmatory factor analyses to provide construct validity support for the factor structure of the Mental Strength Scale (MSS-9).
Keywords: Resilience, Perseverance, Grit, Performance, Mental toughness.

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INTRODUCTION

Measuring mental strength has been target of discussion for several years (Clough et al., 2002; Van Haitsma et al., 2018). In 1918, Major Robert M. Yerkes proposed the development of psychological centres to assess mental strength in military personnel (Yerkes, 1918). Since then, many instruments have been developed to assess mental performance-related variables (Clough et al., 2002; Duckworth et al., 2007; Smith et al., 2008; Van Haitsma et al., 2018). However, until recently there has been a lack of clarity regarding the definition of mental strength and how to assess it (Lorenco-Lima, 2024). Moreover, the overcomplexity of some instruments through the inclusion of several constructs may decrease the objectivity of the assessment and make it unclear for mental performance practitioners what to prioritize when prescribing training plans to optimize mental strength. To overcome these barriers, the Mental Strength Scale was initially designed as a simple tool for field application for mental performance practitioners to determine strategic plans to improve mental strength.

Mental strength definition

Initially, mental strength was discussed as involving two components: perseverance and resilience. Derived from the Latin word *perseverant* (abiding by strictly), perseverance represents one's persistence in pursuing a task regardless of difficulty (Dagnall et al., 2019). Resilience is derived from the Latin word *resile* (*re* = back and *salire* = to jump) and represents one's ability to recover from hardships (Smith et al., 2008). Stemming from these concepts, Lorenco-Lima (2024) defined mental strength as one's ability to persist through obstacles and recover from failures. The relevance of mental strength is based on the notion that the ability to persevere despite barriers and setbacks is one of the qualities people most admire in others (Csikszentmihalyi et al., 2005).

Mental strength conceptualization

Mental strength is best understood through a parallel with well-established concepts and biological training principles in sports science. The adoption of language compatible with sports science may facilitate comprehension, increase acceptance, and decrease stigma among the general population. For instance, to increase muscular strength, muscle fibres must be stressed beyond their current capacity to expand their functionality (Malm et al., 2019). Similarly, the brain must be stimulated beyond its current capacity in order to expand its functionality. Therefore, the improvement of mental strength follows the biological training principles outlined below.

Overload principle

The overload principle represents one of the main factors required for muscular adaptations such as increases in muscle strength and power (Steinhaus, 1933; Kasper, 2019). The term overload describes the stimuli necessary to promote acute response and, over time, chronic adaptation (Kasper, 2019). Psychological overload specifically refers to the stimuli required to promote acute responses and chronic mental strength adaptations. An individual presenting higher mental strength will extend the time to reach psychological fatigue and shorten the recovery time after psychological fatigue.

Adaptation principle

The principle of adaptation is dependent on a person's ability to balance fatigue, fitness, and recovery and describes the process occurring after systematic applications of overloads over time leading to positive chronic adaptations (Fountaine, 2024). As a result of the principle of adaptation, extraneous psychological overloads become less taxing over time due to increased psychological efficiency (i.e., psychological fitness).

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Progression principle

The principle of progression describes the increments in stimulus required to impose overload and sustain continued adaptation (Kasper, 2019). Progression must be appropriately managed through optimal control of the intensity, volume, frequency, and overall workload to prevent "*injuries*" (mental health disorders), resulting from rapid progression, or goal postponement (e.g., confidence optimization) due to a decelerated progression (Kasper, 2019).

Individuality principle

Individuality explains a person's unique ability to adapt to overloads (Schwellnus et al., 2016). Excessive psychological overloads may lead to detrimental effects such as burnout and psychological overtraining (i.e., mental health disorders).

With adequate psychological overload, adaptation, and progression, the initial mental strength baseline may be surpassed. The timeline to determine the adequate level of psychological overload and progression depends on the specificities of the individual. Adequate rest and nutrition are critical to optimizing the development of mental strength.

General and situational mental strength

Similarly to the idea of dispositional and situational elements of self-confidence theorized by Vealey (1986), mental strength can be addressed as general or situational. Situational mental strength explains the individual's behaviour in a specific domain. For instance, one may demonstrate high mental strength in athletics, but present low mental strength in scholarly activities. Moreover, although some inter-context transferability may occur, one can present high mental strength in a particular scholarly subject or sport (e.g., math or volleyball) but low mental strength in a different subject or sport (e.g., literature or judo). General mental strength describes the individual's overall behaviour across the multiple domains in life.

Mental Strength Scale

The Mental Strength Scale was developed as a self-report instrument to measure general mental strength in a sample of 431 participants, including 373 combat sports practitioners (i.e., grapplers and strikers) and 58 non-practitioners (Lorenco-Lima, 2024). The initial scale was developed as 20 items presenting adequate face validity and assessing the two components of mental strength: resilience and perseverance. Ten items were developed to address resilience by assessing the respondents' thoughts about dealing with failure (e.g., "*I'm scared of failing*"). An additional 10 items were developed to address perseverance by assessing the respondents' thoughts about facing challenges (e.g., "*I work hard to overcome challenges*"). After analysis of the internal reliability coefficients, redundancy, and clarity, eight items were dropped (e.g., retained: "*I have overcome challenges in the past*;" dropped: "*I have not overcome any challenges in the past*"). An exploratory factor analysis with the remaining items resulted in the exclusion of two additional items to retain factor loadings over .40. The resulting Mental Strength Scale (Appendix A) included 10 items (5-point Likert), representing two subscales: perseverance (facing obstacles) and resilience (dealing with risk of failure). Total scores were determined by the average of the ten items, with 5 representing high mental strength and 1 representing low mental strength.

STUDY 1

As part of a sequential development of the Mental Strength Scale, study 1 aimed to confirm the initially proposed factor structure in a sample of Brazilian jiu-jitsu and judo athletes. The sample was selected based on the relevance of mental strength in combat sports, where continued practice requires athletes to endure intense training and unexpected results in competitions.

METHODS

Procedures

Data collection for Study 1 was conducted from April 19 to June 29, 2024, via Google Forms. The form was distributed online via Instagram, Facebook posts, and email campaigns. Participants included in the study were male and female, from 18 to 60 years of age, with all experience levels in Brazilian jiu-jitsu and judo, currently engaged in at least one Brazilian jiu-jitsu or judo class per week. Participants answered the demographic (age and biological sex) and training-characteristic questions (combat sports style, training experience in years) followed by the Mental Strength Scale.

Study 1 was conducted anonymously, and no compensation was offered to the respondents. An information sheet was provided to the participants presenting the details of the study. The Liberty University Institutional Review Board exempted this study as outlined in 45 CFR 46:104(d): Category 2. (i). clarifying that the data obtained by the author is recorded in a way that the identity of the human participants cannot readily be ascertained directly or through identifiers linked to the participants (*Electronic Code of Federal Regulations*, 2024).

Participants

Study 1's sample included 630 combat sports participants, representing 502 males (79.7%) and 128 females (20.3%) from 18 to 60 years of age (39.13 ± 9.82). Of the total sample, 420 were Brazilian jiu-jitsu practitioners (66.7%) and 210 judo practitioners (33.3%). Brazilian jiu-jitsu practitioners reported 6.46 ± 5.92 years of experience, and Judo practitioners reported 13.91 ± 12.87 years of experience.

Materials

The Mental Strength Scale is a 10-item (Appendix A), 5-point Likert scale developed to assess the athlete's mental strength (Lorenco-Lima, 2024). Participants were asked to mark the response that best represented their thoughts and behaviours over the past month. Items 3, 6, 7, and 10 were positively worded, with 1 representing "*strongly disagree*" and 5 "*strongly agree*." Items 1, 2, 4, 5, 8, and 9 are negatively worded and reverse coded. Questions represent two subscales, dealing with the risk of failure (items 1, 2, 4, 5, 8, and 9) and facing obstacles (items 3, 6, 7, and 10). Total scores were determined by the average of the item responses, with higher scores indicating higher mental strength. In previous studies, the Mental Strength Scale presented Cronbach's alpha of .81, in addition to convergent validity with measures of resilience and grit (Lorenco-Lima, 2024).

Analysis

Based on the hypothesized structure of mental strength construct as previously outlined, two confirmatory factor analysis (CFA) models were tested. *Model 1* was a two-factor model in which items 1, 2, 4, 5, 8, and 9 were loaded onto the Dealing with Risk of Failure (DRF) factor, and items 3, 6, 7, and 10 loaded onto the Facing Obstacles (FO) factor. *Model 2* was a unidimensional model in which all 10 items loaded onto a single mental strength factor. Maximum likelihood estimation was used for both models as this estimation method performs well in most circumstances (including when some model misspecification is present; Finney & DiStefano, 2013; Olsson et al., 1999).

Assessing model-data fit

To assess the absolute fit of the models, several statistics were examined. First is the chi-square statistic, which tests the significance of the difference between the observed and model-implied covariance matrices. Because the large sample size for this study will result in increased power, the chi-square will likely be

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statistically significant even if the actual difference between the covariance matrices is negligible. Thus, additional measures were considered, including the standardized root mean square residual (SRMR), which is a standardized summary of the covariance residuals; SRMR values of .08 and below are generally considered indicative of good fit (Hu & Bentler, 1999). The root mean square error of approximation (RMSEA) assesses model misfit per degrees of freedom. Recommendations regarding cutoff values are mixed, but generally a value of .06 is considered good whereas values greater than .10 are poor (Browne & Cudeck, 1993; Hu & Bentler, 1999). Finally, the comparative fit index (CFI) was examined, which compares the model of interest to an independence (null) model. A recommended cutoff value is .95, with higher values indicating better fit (Hu & Bentler, 1998; 1999). Besides considering the chi-square value and fit indices, the residuals to assess areas of local misfit were also examined.

To assess the relative fit of the models, a chi-square difference test for the nested models was performed, which is a significance test of the difference between two chi-square values, with degrees of freedom equal to the difference in degrees of freedom between the two models. Akaike's information criteria (AIC) was also examined, which is based on deviances and provides information regarding both model fit and parsimony. Lower values are indicative of better fit (Hu & Bentler, 1998).

RESULTS

Confirmatory factor analysis

In terms of absolute fit, chi-square and fit index values are presented in Table 1. As expected, given the large sample size, the chi-square values for all four models were statistically significant. The SRMR value for the two-factor model was below the .08 cutoff, but the one-factor model was not. RMSEA for both models was poor, being greater than 0.10; and CFI values for both models were also below the 0.95 cutoff, though the two-factor model value was better than the one-factor model.

Table 1. Absolute and relative fit measures.

	χ^2	df	SRMR	RMSEA	CFI	AIC	$\Delta\chi^2$	Δdf	*p-value*
2-Factor	256.33**	34	0.070	0.102	0.864	298.33	-	-	-
1-Factor	593.65**	35	0.107	0.159	0.659	633.65	337.32	1	<.001

Table 2. Observed 2-factor model correlations (Bottom) and model correlation residuals (Top).

	3	6	7	10	1	2	4	5	8	9
3	-	-.004	-.032	-.015	.081	.254	.018	.023	.16	.073
6	.503	-	.039	-.019	-.066	.032	-.141	-.033	.027	-.052
7	.448	.553	-	.019	-.036	-.015	-.115	-.078	-.017	-.026
10	.365	.387	.404	-	.04	.067	-.082	.016	.079	.18
1	.278	.145	.164	.198	-	.072	.036	-.035	-.052	-.045
2	.429	.22	.163	.208	.444	-	-.115	-.063	.062	.041
4	.225	.081	.095	.084	.475	.275	-	.135	-.008	-.019
5	.207	.164	.109	.164	.356	.285	.545	-	-.063	-.021
8	.324	.203	.15	.211	.297	.372	.358	.263	-	.06
9	.23	.116	.134	.306	.289	.338	.331	.291	.338	-

Note. Items 3, 6, 7, and 10 loaded onto the Facing Obstacles (FO) factor. Items 1, 2, 4, 5, 8, and 9 load onto the Dealing with Risk of Failure (DRF) factor.

In terms of relative fit, the significant chi-square difference tests (see Table 1) indicate that the more parsimonious model (e.g., the one-factor model) fits statistically significantly worse than the more complex

model (e.g., the two-factor model). Thus, the two-factor model fit best according to the relative fit information. This is further supported by the AIC values in Table 1. However, given the overall poor absolute fit of both models, the two-factor model was not considered to fit sufficiently well to champion.

In order to determine the reason for the poor misfit, patterns of observed correlations as well as the correlation residuals were examined (observed – model-implied; see Table 2). Based on this, it was determined that the issue is likely due to a little-discussed assumption of CFA models known as proportionality constraints. Proportionality constraints mean that the correlation of any two items with a third item must be proportional to the correlation of those same two items with a fourth item. The extent to which these constraints are violated will result in model misfit because the model will be unable to reproduce the correlations well. Proportionality constraint violations can be best seen via pairs of items with especially high or low correlations within or across factors, compared to other pairwise correlations (D. Bandalos, personal communication, August 6, 2024).

To observe the proportionality constraint violations in action, consider the correlation between items 2 and 3 (r = 0.429), and 9 and 10 (r = 0.306) in Table 2. Each of these two pairs of items are on opposite factors yet have higher correlations with each other than with other items on their own factor. Items 2 and 4 (r = 0.275) are in the same factor yet have the relatively lowest pairwise correlation. In contrast, items 4 and 5 (r = 0.545) have one of the highest correlations within their factor, which makes it difficult for the model to reproduce the observed correlation. These patterns may suggest some sort of method effect (e.g., items with too similar meaning) for only some of the items, thus resulting in too high and too low correlations for some pairs of items but not others. As a result, edits to the scale items were needed.

STUDY 2

Based on the poor fit of the initial Mental Strength Scale factor structure, Study 2 aimed to make edits to the scale and reassess its structure in a sample of the general population.

METHOD

Editing the scale

After examining the item content and the specific issues with the scale in Study 1, two items were dropped due to a lack of the explicit behavioural aspect of mental strength (Item 2: "*I hate challenges*" and Item 4: "*I am scared of failing*"). Additionally, some of the remaining items were rephrased to address potential issues with double-barrelled wording. Moreover, 12 additional items were developed and included to address the behavioural characteristics of mental strength, which is defined as a person's ability to persist through obstacles and recover from failures (Lorenco-Lima, 2024).

After rephrasing 8 original items (items O1 to O8) and adding 12 new items (resilience: items N1 to N6; perseverance: items N7 to N12), the new scale was ready for administration (Appendix B).

Procedures

Data collection for Study 2 was conducted from September 18 to October 23, 2024, via Google Forms. The form was distributed online via Amazon mTurk. The participants included in the study were male and female representatives of the United States general population from 21 to 60 years of age. Participants answered two demographic questions (age and biological sex) followed by the Mental Strength Scale.

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Study 2 was conducted anonymously, and participants were compensated ($0.50) per form via Amazon mTurk. The necessary modifications were submitted and approved by Liberty University's Institutional Review Board.

Participants

Study 2 included 316 representatives of the United States general population, representing 215 males (68%) and 101 females (32%) from 21 to 60 years of age (32.95 ± 7.05).

Analysis

Using the data from the new sample and updated scale, a principal axis factoring exploratory factor analysis (EFA) was performed to determine what factor structure might work best with the old and new Mental Strength Scale items. A direct obliging rotation was used, which is an oblique rotation method; this means that the factors can correlate with one another, which made theoretical sense in the context of the Mental Strength Scale – that is, if there is more than one factor suggested by the EFA, it would be expected that they correlate with one another.

To determine the number of factors to retain from the EFA, consideration was given to the variance explained by each extracted factor, the scree plot (which provides a graphical representation of the factor eigenvalues), the factor pattern coefficients (i.e., loadings) for each item, and the item content/interpretability of the factor(s) identified.

RESULTS

Exploratory factor analysis

Table 3 and Figure 1 together suggest that a maximum of two factors is the likely best solution. Specifically, there is a notable "*levelling off*" of the variance explained by factor 3 and above.

Table 3. Variance explained by the first four extracted factors.

Factor	Variance explained	Eigenvalue % of variance
1	5.49	27.46%
2	2.35	11.73%
3	1.19	5.95%
4	1.08	5.39%

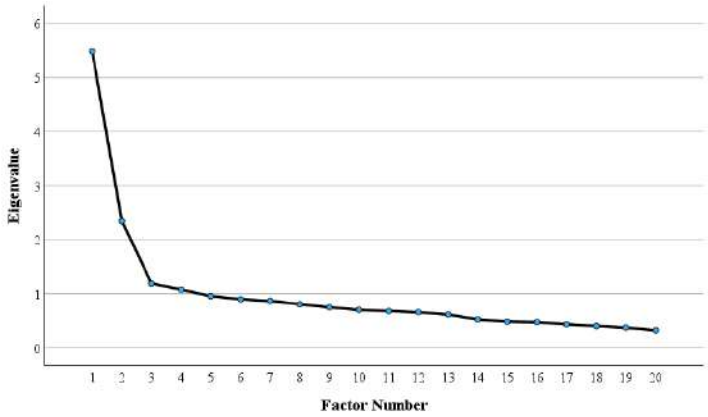

Figure 1. Screen plot for maximum number of extracted factors.

The inclusion of two factors is further supported by the factor pattern matrix (Table 4), which presents the factor loadings for each item on the first four factors. The shaded cells in Table 4 represent items with loadings on their specific factor of +0.35 or greater, indicating that the item loads onto the factor adequately. Note that items with strong loadings on factor 1 do not show strong positive loadings on any of the other factors, which is an indication of a good simple structure EFA solution. The same is true for items loading on factor 2. One exception to this pattern is item N12, which has a strong loading on factor 3 and a moderate loading on factor 1, suggesting it may be a good candidate for removal pending examination of the item content.

Table 4. Factor pattern matrix.

Item	Factor			
	1	2	3	4
N1	.467	.137	-.119	-.231
N2	.048	-.026	.013	-.474
N3	.826	-.067	-.115	.119
N4	.002	-.008	.040	-.607
N5	.504	-.036	-.036	-.168
N6	.578	-.036	.065	-.027
N7	.299	.030	.048	-.367
N8	.443	.078	.225	-.055
N9	.345	-.095	-.001	-.280
N10	.140	.064	.211	-.497
N11	.481	.047	-.056	-.096
N12	.306	.013	.477	-.172
O1	.251	.087	-.168	-.363
O2	.064	.512	-.390	.061
O3	.234	.005	-.355	-.434
O4	-.100	.780	.028	-.100
O5	.435	-.107	.175	-.044
O6	-.178	.610	.010	-.177
O7	.385	.019	.111	-.156
O8	.126	.587	.056	.192

Upon examination of the item content, a decision was made to drop the mildly cross-loading item N12. This item stated, "*I am able to stick to tasks even when they become challenging or boring*." The inclusion both adjectives "*challenging*" and "*boring*" could make the item double-barrelled. Additionally, the item seemed to be assessing a slightly different construct than the rest of the items, a conclusion that was supported by the fact it was the only item loading strongly on factor 3.

This left two factors for consideration, with factor 2 containing only four items. Examination of the item content made it immediately apparent that these four items are all negatively oriented – that is, an *Agree* response means that the respondent is *lower* on the construct of mental strength. Specifically, the items are:

- O2: I don't like to put myself in situations where I may not succeed.
- O4: Challenges make me doubt myself.
- O6: If I believe I can fail, I may not finish.
- O8: I have a hard time finding the motivation to overcome challenges.

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Not only are these items all negatively oriented, but they are also in fact the only negatively oriented items on the scale. This is strong evidence that factor 2 is resulting solely from a method effect of the item wording. Although including negatively oriented items on a scale can provide benefits such as serving as an attention check or encouraging respondents to think more deeply about their responses, when these types of items cluster together in a method factor it can be argued that they are doing more harm than good. The rewording of the items to a positive orientation was considered; but ultimately, they were dropped as they do not add much to the scale in terms of the specific content they are assessing. As a result, a one-factor solution is championed, with items N1, N3, N5, N6, N8, N9, N11, O5, and O7 being retained (Appendix A).

Reliability

To provide additional support to the championed one-factor solution, Cronbach's alpha was computed for the retained items. This resulted in an alpha of .81, which represents good internal consistency reliability.

DISCUSSION AND CONCLUSIONS

Study 1 aimed to confirm the initially proposed 2-factor structure of the Mental Strength Scale in a sample of Brazilian jiu-jitsu and judo athletes. CFA results indicated that neither the hypothesized 2-factor structure nor the unidimensional model were a good fit for the data. Based on the poor fit of the initial factor structure of the Mental Strength Scale, Study 2 aimed to propose edits to the scale and reassess its structure in a sample of the general population. Based on the EFA results, a one-factor solution was championed with nine remaining items. The one-factor solution supports the idea that mental strength may be a unidimensional construct rather than being composed of resilience and perseverance as separate constructs. Thus, the Mental Strength Scale – 9 (MSS-9) is championed pending further validation using additional samples and confirmatory factor analyses (Appendix C).

The unidimensional characteristic of mental strength is supported by the idea that perseverance and resilience share a conceptual similarity that enables individuals to progress despite obstacles (Turbeville, 2021). Both constructs are essential for mustering the internal and external resources necessary to overcome adversities (Tsai & Morissette, 2022). Although conceptually different, when assessed via self-reported items, the conceptual similarities may overshadow the differences making them too subtle to generate two distinct variables.

These studies present some limitations which provide groundwork for future studies. First, further validity evidence is needed. This should include both convergent validity evidence with measures of related constructs such as resilience and grit, as well as divergent validity evidence with measures of constructs such as social responsibility. Moreover, predictive validity studies may determine the usefulness of mental strength in contexts involving performance, well-being and mental health. Additionally, as a construct that is not expected to change substantially over time, the scale would benefit from the assessment of test-retest reliability to provide further reliability evidence.

Lastly, although the exploratory factor analysis results made a compelling argument for a one-factor solution, a follow-up CFA is needed to provide support for the factor structure of the retained items. Thus, future studies using these items with a new sample should test a one-factor CFA model to support the findings outlined here before the scale can be widely used for research purposes.

AUTHOR CONTRIBUTIONS

Conceptualization, L.d.L.-L., S.A.G., and E.M.W.; methodology, L.d.L.-L.,S.A.G., and E.M.W.; software, L.d.L.-L., and E.M.W.; formal analysis, L.d.L.-L., and E.M.W.; investigation, L.d.L.-L.; resources, L.d.L.-L.; data curation, L.d.L.-L., and E.M.W.; writing—original draft preparation, L.d.L.-L., S.A.G., and E.M.W.; writing—review and editing, L.d.L.-L., S.A.G., and E.M.W.; visualization, S.A.G., and E.M.W.; supervision, S.A.G., and E.M.W.; project administration, L.d.L.-L. All authors have read and agreed to the published version of the manuscript.

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DISCLOSURE STATEMENT

No potential conflict of interest was reported by the authors.

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APPENDIX A. MENTAL STRENGTH SCALE – ORIGINAL VERSION

Thinking about your athletic and exercise engagement, mark the box that best represents your thoughts over the past month. There is no right or wrong answer, just answer it to the best of your ability!

Mark one box per row that best describes your thoughts		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
MSS 1	Challenges make me doubt myself (DRF)	5	4	3	2	1
MSS 2	I hate challenges (DRF)	5	4	3	2	1
MSS 3	I enjoy opportunities to challenge myself (FO)	1	2	3	4	5
MSS 4	I am scared of failing (DRF)	5	4	3	2	1
MSS 5	It's hard to recover from failure (DRF)	5	4	3	2	1
MSS 6	Challenges make me stronger (FO)	1	2	3	4	5
MSS 7	I have overcome challenges in the past (FO)	1	2	3	4	5
MSS 8	I don't like to get out of my comfort zone (DRF)	5	4	3	2	1
MSS 9	If it's hard, I may not finish it (DRF)	5	4	3	2	1
MSS 10	I work hard to overcome challenges (FO)	1	2	3	4	5

Note. FO = Facing Obstacles; DRF = Dealing with Risk of Failure.

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APPENDIX B. SCALE MODIFICATIONS

Mental Strength Scale		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
O1	Dealing with failures makes me stronger. (DRF)	1	2	3	4	5
O2	I don't like to put myself in situations where I may not succeed. (DRF)	5	4	3	2	1
O3	I enjoy opportunities to challenge myself. (FO)	1	2	3	4	5
O4	Challenges make me doubt myself. (FO)	5	4	3	2	1
O5	When I don't succeed at something, I recover from failure quickly. (DRF)	1	2	3	4	5
O6	If I believe I can fail, I may not finish. (DRF)	5	4	3	2	1
O7	When I face obstacles, I work hard to overcome them. (FO)	1	2	3	4	5
O8	I have a hard time finding the motivation to overcome challenges. (FO)	5	4	3	2	1
N1	Instead of dwelling on failures, I focus on learning from them and making improvements. (DRF)	1	2	3	4	5
N2	I use setbacks as opportunities to grow and develop new skills. (DRF)	1	2	3	4	5
N3	I recover quickly from adversity. (DRF)	1	2	3	4	5
N4	I use setbacks as motivation to work harder and achieve my goals. (DRF)	1	2	3	4	5
N5	I have a strong capacity for bouncing back from adversity. (DRF)	1	2	3	4	5
N6	I am resilient and able to recover quickly from setbacks. (DRF)	1	2	3	4	5
N7	I am persistent in pursuing my goals, even when faced with obstacles. (FO)	1	2	3	4	5
N8	I tend to complete tasks regardless of how long they take. (FO)	1	2	3	4	5
N9	I am persistent in completing tasks, even when I lack motivation. (FO)	1	2	3	4	5
N10	I am able to overcome obstacles and continue working towards my objectives. (FO)	1	2	3	4	5
N11	I am determined to achieve my goals and will not give up easily. (FO)	1	2	3	4	5
N12	I am able to stick to tasks even when they become challenging or boring. (FO)	1	2	3	4	5

Note FO = Facing Obstacles; DRF = Dealing with Risk of Failure

APPENDIX C. MENTAL STRENGTH SCALE (MSS-9) – CHAMPIONED VERSION

Mark the box that best represents your behaviours over the past month.

Mental Strength Scale		Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
MSS1	Instead of dwelling on failures, I focus on learning from them and making improvements.	1	2	3	4	5
MSS2	I recover quickly from adversity.	1	2	3	4	5
MSS3	I have a strong capacity for bouncing back from adversity.	1	2	3	4	5
MSS4	I am resilient and able to recover quickly from setbacks.	1	2	3	4	5
MSS5	I tend to complete tasks regardless of how long they take.	1	2	3	4	5
MSS6	I am persistent in completing tasks, even when I lack motivation.	1	2	3	4	5
MSS7	I am determined to achieve my goals and will not give up easily.	1	2	3	4	5
MSS8	When I don't succeed at something, I recover from failure quickly.	1	2	3	4	5
MSS9	When I face obstacles, I work hard to overcome them	1	2	3	4	5

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ORIGINAL ARTICLE

Key performance indicators for success in the 2024 Olympic men's basketball tournaments

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ABSTRACT

The purpose of the present study was to examine differences between winning and defeated basketball teams in the 2024 Men's Olympic Tournament (OT) (n = 26) and the 2024 Olympic Qualifying Tournaments (OQT) (n = 36). The differences were assessed in three selected indicators: 3-point percentage (3PT%), rebound percentage (REB%), and turnover percentage (TOV%). T test has shown significant differences in 3PT% (p < .01) and REB% (p < .01) at OT. In OQT, we found statistically significant differences between winning teams and defeated in all variables (p < .01). Binary logistic regression identified in OQT all three independent variables as significant predictors of winning. If 3PT% and REB% increased by one unit, the odds of winning increased by 13% and 29%, respectively. On the other hand, if TOV% increased by one unit, the odds of winning decreased by 24%. In the OT, the binary logistic regression identifies only REB% as a significant predictor of winning. One unit of increase in REB% was associated with a 25% greater chance of winning. Coaches should focus on 3-point shooting efficiency, rebounding control, and minimizing turnovers, as these factors significantly affect the likelihood of winning basketball games.

Keywords: Teams sports, Performance indicators, Binary logistic regression, 3PT%, REB%, TOV%.

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INTRODUCTION

3-point shooting has become one of the most important aspects of modern basketball, and its importance continues to grow. In recent years, basketball teams have increasingly focused on making as many attempts as possible from 3-point range, as several studies have shown that successful 3-point shooting can significantly affect the outcome of a game. Various studies show that 3-point shooting increases the total number of points scored and, in principle, expands the opponent's defence. Consequently, it can open up space in a defined territory (Sampaio & Janeira, 2003; Piras, 2024). 3-point shooting has become a key element of offensive strategies, and teams that can shoot effectively from this distance tend to dominate games. Today, 3-point shooting is considered an essential aspect of a successful game plan, with coaches and players needing to understand not only the shooting technique but also the psychology and visual aspects that affect the success of this shooting (Piras, 2024). It has been found that the team with a higher percentage of successful 3-point shooting is more likely to win (Cabarkapa et al., 2022; Conte et al., 2018; Garcia et al., 2013). Vencúrik et al. (2021) found that fatigue and defensive pressure significantly affect the kinematic parameters of the 3-point shot. Players exhibit kinematic differences, such as increases in jump height and changes in shooting technique, to maintain consistent performance under these conditions. In close games, 3-point shooting success rate and number of 3-point shots are key factors that influence the outcome (Csataljay et al., 2012). High 3-point shooting success rates have shown that teams that can maintain it consistently tend to dominate at crucial moments in the game (Cabarkapa et al., 2022). It has also been shown that players who focus on improving their 3-point shooting success rate tend to increase their overall offensive efficiency.

Each shot is followed by another game activity, which is rebounding. Rebounds, especially defensive rebounds, are critical factors in crucial moments of the game. Teams that perform better in rebounding have a higher probability of winning (Csataljay et al., 2012; Conte et al., 2018; Garcia et al., 2013; Urkovic et al., 2005). Studies suggest that defensive rebounds are among the most essential indicators differentiating a team's winning and defeating (Cabarkapa et al., 2022). Mikołajec et al. (2013) found that a team that can secure more defensive rebounds tends to have better game outcomes. It has also been shown that rebounding is vital for limiting the opponent's second chances of scoring, and so is the number of turnovers, as having a high number of turnovers allows the opponent to attack more often. Turnovers are considered one of the most crucial team performance indicators. In basketball, every possession of the ball is valuable. A high number of turnovers can lead to a potential loss of points and reduce the chances of winning. Scientific evidence suggests that a team that minimizes turnovers has more control over the game and can use its offensive capabilities more effectively (Mikołajec et al., 2013). Various factors, including poor decisions, lack of communication between players, and pressure from the defence, can cause turnovers. The players need to know what their weaknesses are offensively and make an effort to practice decision-making. Studies show that fewer turnovers are associated with a higher probability of winning (Mikołajec et al., 2013; Cabarkapa et al., 2022). In close games, it has been found that a higher turnover rate can significantly affect the outcome (Csataljay et al., 2012).

Based on the findings, this study aimed to investigate the differences between the winning and defeated teams by our selected two positive parameters: 3-point shooting (3PT%) and rebounds expressed using the advanced statistical method REB%, and one negative: turnovers expressed as TOV% in the 2024 Men's Basketball Olympic Tournament (OT) and the 2024 Men's Basketball Olympic Qualifying Tournaments (OQT). We assumed that if the number of positive indicators increases, the chance of winning increases; conversely, the chance of winning decreases as the number of negative indicators increases.

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MATERIAL AND METHODS

Participants

The examined dataset included 26 games played in the OT, while 36 were played in the OQT. The overall number of observed games was 62. OQT took place in four host cities, where 24 teams were divided into four groups (group phase), with the top teams advancing to the play-off, where the winners of the semifinals played for the four qualifying spots in the OT. The total number of games played in the OQT was 36, the number of 3-point attempts was 2022, the number of 3-points made was 691, the number of rebounds was 2611, and the number of turnovers was 901. In the OT, the top 12 teams from all over the globe participated and were divided into three groups. The number of games was 26, where the number of 3-point attempts was 1547, the number of 3-points made was 566, the number of rebounds was 1942, and the number of turnovers was 706.

Procedures

From each game, we tracked 3PT%, REB%, and TOV% for both winning and defeated teams (Kubatko et al., 2007; Oliveira et al., 2024; Scrucca et al., 2024; Rowe et al., 2024). 3-point shooting was selected because it represents a current trend in global basketball, and as its efficiency increases, so does its impact on the overall outcome. Rebounds are directly related to shooting and ball possession. Turnovers represent a negative factor that deprives a team of ball possession.

Statistical data were obtained by analysing the game statistics of games played in the OT and in the OQT from the official FIBA websites (FIBA, 2024).

Formula for calculating TOV%:

$$TOV\% = (TOV / FGA + TOV – ORB * 0,44 + FTA) * 100$$

Note: TOV% – turnover percentage; FGA – field goal attempted; TOV – turnover; ORB – offensive rebound; FTA – free throws attempted.

Formula for calculating REB%:

$$REB\% = (REB_a / REB_a + REB_b) *100$$

Note: REB% – rebound percentage; REB_a – winning team; REB_b – defeated team.

Statistical analysis

Data are presented as mean ± standard deviation. Shapiro-Wilk's test checked the normality of distribution. Normality was not violated. Therefore, the parametric independent t test was used to identify differences in selected variables (3PT%, REB%, and TOV%) between winning and defeated teams. Cohen's d and 95% confidence intervals (95% CI) also expressed effect sizes for differences. Cohen's d was interpreted as a trivial (<0.2), small (0.2–0.5), medium (0.5–0.8), and large (>0.8) effect (Cohen, 1988).

The binary logistic regression (enter method) was used to predict the result of the game based on independent variables (3PT%, REB%, and TOV%) (Malek et al., 2018). Therefore, the game's outcome could acquire only two values, i.e., 0–lose or 1–win. The maximum likelihood method was used to estimate the regression coefficients. Wald's test verified the statistical significance of the regression coefficients, and 95%

confidence intervals were constructed for the likelihood ratio. Nagelkerke R-square was used to assess the proportion of variance in the dependent variable (game's outcome) explained by the predictors (3PT%, REB%, and TOV%). A significance level was set for $p \leq .05$. All statistical tests were calculated using IBM SPSS Statistics 29 (IBM Corp., New York, USA).

RESULTS

Descriptive statistics and differences between winning and defeated teams in 3PT%, REB%, and TOV% are shown in Table 1. In the OQT, we found statistically significant differences between winning and defeated teams in all variables, with medium to large effect sizes. There were substantial differences in 3PT% and REB% in OT, with medium and large effect sizes.

Table 1. Descriptive statistics and differences in selected variables between winning and defeating teams.

Variable	Winners	Defeated	*p*-value	ES (95% CI)
Olympic Qualifying Tournaments				
3PT%	37.8 ± 7.3	30.8 ± 8.6	<.001	0.89 (0.41; 1.37)
REB%	53.5 ± 6	46.5 ± 6	<.001	1.16 (0.65; 1.65)
TOV%	13.6 ± 4.3	15.9 ± 4.3	.03	-0.54 (-1.01; -0.07)
Olympic Games Tournament				
3PT%	39.5 ± 10.2	33.7 ± 5.3	.01	0.71 (0.15; 1.27)
REB%	52.8 ± 5.6	47.2 ± 5.6	<.001	1.02 (0.44; 1.59)
TOV%	15.3 ± 3.8	15.5 ± 3.7	.86	-0.05 (-0.59; 0.49)

Note. 3PT – 3-point shooting percentage; REB% – rebound percentage; TOV% – turnover percentage; p – level of statistical significance; ES – effect size; CI – confidence intervals

Table 2. Estimation of regression model parameters for winning with explanatory variables.

Variable	B	SE	Wald	df	*p*-value	OR	95% CI for OR	
							Lower	Upper
Olympic Qualifying Tournaments								
3PT%	0.12	0.05	6.59	1	.01	1.13	1.03	1.24
REB%	0.25	0.07	11.42	1	<.001	1.29	1.11	1.47
TOV%	-0.28	0.1	7.94	1	.005	0.76	0.63	0.92
Olympic Games Tournament								
3PT%	0.07	0.05	1.99	1	.16	1.07	0.98	1.17
REB%	0.23	0.08	7.09	1	.008	1.25	1.06	1.48
TOV%	-0.11	0.1	1.32	1	.25	0.9	0.74	1.08

Note. B – standardized beta weights; SE – standard error of the estimate; Wald – values of Wald's test; df – degrees of freedom; p – the statistical significance of regression coefficients; OR – odds ratio; CI – confidence interval

Binary logistic regression identified in OQT all three independent variables as significant predictors of winning. Higher 3PT% and REB% and lower TOV% are associated with a greater chance to win. If 3PT% and REB% increased by one unit, the odds of winning increased by 13% and 29%, respectively. On the other hand, if TOV% increased by one unit, the odds of winning decreased by 24%. Nagelkerke R-square has a value of .552; therefore, the predictor variables explain 55.2% of the variance in the dependent variable. In the OT, the binary logistic regression identified only REB% as a significant predictor of winning. One unit of increase in REB% was associated with a 25% greater chance of winning. Nagelkerke R-square for OT has a value of .383, which means that the predictor variable explains 38.3% of the variance in the dependent

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variable. Estimation of regression model parameters with explanatory variables, their standard errors, and the odds ratios is given in Table 2.

DISCUSSION

Our study confirmed differences in 3PT% and REB% between winning and defeated teams, with medium and large effect sizes. In the OQT, we found statistically significant differences between winning and defeated teams in all variables, with medium to large effect sizes. Paulaskas et al. (2018) did not find significant differences in 3-point shooting efficiency between players competing in the NBA and the EuroLeague. However, 3-point shooting was identified as a key determinant in the NBA play-off (Mateus et al., 2018). Dogan et al. (2019) found that 3-point shooting efficiency significantly increased with each additional EuroLeague round, impacting game outcomes. A higher number of successful 3-point shots was observed in winning teams than in defeated teams (Ibáñez et al., 2008; Karipidis et al., 2001). Sampaio et al. (2010) analysed the 3-point shooting efficiency of Team USA at OT in Beijing in 2008 and found that it was a key factor in their gold medal run. In close games, 3-point shooting efficiency was identified as a decisive factor influencing game outcomes (Csataljay et al., 2009). Even in youth tournaments, such as the U16 category, the significance of 3-point shooting efficiency in determining game outcomes was confirmed. Teams improved their 3-point shooting accuracy in critical moments, contributing to their victories (Lorenzo et al., 2010). Milanović et al. (2016) show that a high percentage of 3-point shots is essential for achieving positive results. Teams that use 3-point shots effectively tend to win more games and have better point differentials. However, not all studies unanimously confirm the strong relationship between 3-point shooting efficiency and positive game outcomes. Various studies analysing different tournaments and age categories have not always supported this relationship (Ibáñez et al., 2009; Trninić et al., 2012; Mikołajec et al., 2013; Sampaio et al., 2009). Nevertheless, these studies agree that rebounding is one of the most critical factors in determining game outcomes.

Rebounding is one of the most important individual skills. While individual success in rebounding does not determine team success, collective rebounding effort significantly increases the chances of gaining possession after a missed shot. Comparing NBA and EuroLeague players revealed that NBA players had a significantly higher number of defensive rebounds (Sampaio et al., 2010). Mikołajec et al. (2013) found that winning NBA teams had more defensive rebounds. Similarly, in NBA play-off games, winning teams demonstrated significantly higher defensive rebounding numbers (Mateus et al., 2018). Defensive rebounds prevent second-chance scoring opportunities and control the game's tempo. Teams with a higher number of defensive rebounds tend to win more frequently (Csataljay et al., 2009; Ibáñez et al., 2009; Dogan et al., 2019; Trninić et al., 2002; Lorenzo et al., 2010; Mateus et al., 2018; Mikołajec et al., 2013; Sampaio et al., 2009; Ibáñez et al., 2008; Karipidis et al., 2001). Although these studies did not explicitly mention the REB% metric, they highlight the importance of rebounding for team success. Our study confirmed this relationship using the REB% indicator, including offensive and defensive rebounds.

Similarly, previous studies have not confirmed a strong relationship between turnovers and game outcomes (Paukauskas et al., 2018; Sampaio et al., 2010; Csataljay et al., 2009; Trninić et al., 2002; Mateus et al., 2013; Mikołajec et al., 2013; Karipidis et al., 2001). However, Dogan et al. (2019) found that minimizing turnovers was crucial for teams advancing from the Top 16 to the EuroLeague play-offs. This relationship was also confirmed by Ibáñez et al. (2009), Dogan et al. (2009), Lorenzo et al. (2010), Sampaio et al. (2009), and Ibáñez et al. (2008). While our study established a direct relationship between turnovers and game outcomes only in OQT, we still emphasize that reducing turnovers is a crucial aspect of the game at any level.

CONCLUSION

This study aimed to identify differences in three indicators for winning and defeated teams in OQT and OT. Our findings showed significant differences between winning and defeated teams in three parameters, 3PT%, REB%, and TOV% in OQT. These parameters also proved to be significant predictors of winning. Increased 3PT% and REB% increased a team's probability of winning, while increased TOV% decreased the likelihood of winning. In OT, we found that REB% is the only significant predictor of winning. These findings could help basketball coaches and performance analysts, providing concrete statistics to focus on when evaluating a team's performance over a game or tournament. In addition, it would be useful to examine the long-term trends of these parameters on the overall success of teams at different stages of tournaments. Our study emphasizes the importance of using advanced statistics rather than absolute numbers. While traditional analyses often rely on absolute values as predictors of team success, advanced statistics accurately reflect individual contexts within a given criterion, offering more profound insights into performance evaluation.

AUTHOR CONTRIBUTIONS

Lubor Tomanek and Tomas Vencurik and Aleksandar Selmanovic conceived and designed the investigation, Tomas Vencurik and Stefan Suja analysed and interpreted the data, Lubor Tomanek and Stefan Suja drafted the manuscript and management. Stefan Suja collected data. All authors read and approved this manuscript before publication.

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No potential conflict of interest was reported by the authors.

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REVIEW ARTICLE

Exceeding limits in sports engineering: The bio-digital-material triad paradigm in the Asian sports performance revolution

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ABSTRACT

This review article explores the innovative breakthroughs of exceeding limits in sports engineering within the context of the Asian sports performance revolution, with a particular focus on advancements in bio-enhancement technologies, neural interfaces, quantum computing, metamaterial equipment, digital twins, predictive medicine, gut microbiota, geopolitical technology, disaster medicine, and civilization-level technological spillovers. By analysing empirical data across multiple dimensions, the article examines how these technologies converge and drive the evolution of sports science, creating a comprehensive logical chain from fundamental research to commercial application, thus providing new pathways for enhancing athlete performance. The significance of these advancements lies not only in their potential to revolutionize athletic training and competition but also in addressing existing challenges and limitations within the field. This review aims to elucidate the interconnections among these cutting-edge technologies and highlight their collective impact on future developments in sports performance.

Keywords: Exceeding limits in sports engineering, Bio-enhancement technologies, Neural interfaces, Quantum computing, Predictive medicine.

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INTRODUCTION

The realm of sports science is undergoing a profound transformation, largely driven by the rapid advancements in technology. The convergence of biological, digital, and material sciences—termed Transcendent Sports Engineering—is at the forefront of this revolution. This emerging field aims to enhance athletic training and performance through an integrative approach that leverages innovations in biotechnology, digital analytics, and advanced materials. The objective of this review is to systematically explore the progress in these technologies, their interconnections, and practical applications that could lead to significant improvements in athletic performance.

The integration of biological technologies into sports science has been particularly impactful. Genetic research has identified specific polymorphisms associated with athletic traits, which raises ethical considerations regarding gene doping and genetic predispositions to injuries (John et al., 2020). For instance, the ACTN3 gene plays a critical role in muscle fibre composition, influencing an athlete's capability in power sports. This biological insight not only informs training regimens but also poses questions about the future of genetic testing in sports. The implications of such advancements extend beyond performance enhancement; they also encompass injury prevention strategies, as understanding genetic predispositions can help tailor training programs to minimize risks (Uttamchandani & Phansopkar, 2024).

Digital technologies, particularly wearable sensors and data analytics, are revolutionizing how athletes train and compete. Wearable devices can monitor physiological parameters in real-time, providing athletes and coaches with critical feedback to optimize performance (Liu & Wang, 2023). The data collected can be analysed to identify patterns, predict injuries, and tailor training loads to individual needs. Moreover, advancements in machine learning and artificial intelligence are being harnessed to process vast amounts of data, leading to more personalized training approaches that account for an athlete's unique physiological responses (Schwarz et al., 2021). This digital transformation is not only about collecting data but also about making informed decisions based on comprehensive analytics, which could potentially redefine training methodologies.

Material science has also made significant strides that directly impact sports performance. Innovations in smart materials, such as temperature-responsive textiles and advanced polymers, are enhancing athletic gear's functionality and comfort (F. Wang et al., 2024). For instance, the development of robust sensing textiles that can monitor body temperature and movement in extreme environments opens new avenues for athlete safety and performance optimization. These materials can adapt to varying conditions, providing athletes with real-time feedback on their physiological state and environmental interactions. Furthermore, the application of 3D printing technology in creating customized sports equipment is revolutionizing how gear is designed and manufactured, allowing for personalized fit and function that can enhance performance and reduce injury risk (Soltani et al., 2020).

The intersection of these three domains—biological, digital, and material technologies—creates a synergistic effect that has the potential to revolutionize athletic performance. For example, integrating genetic insights with digital monitoring and advanced materials can lead to a holistic training approach that is both personalized and adaptive, addressing the unique needs of each athlete. This triadic convergence not only enhances performance but also emphasizes the importance of safety and injury prevention, which are critical in high-stakes competitive environments.

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In conclusion, the advent of Transcendent Sports Engineering represents a paradigm shift in sports science, where the fusion of biological, digital, and material technologies is set to redefine athletic training and performance. This review aims to elucidate the advancements in these fields and their interrelationships, providing a comprehensive understanding of how they can be harnessed for the future of sports performance. As we continue to explore these innovations, it is essential to consider the ethical implications and strive for a balance between enhancing performance and maintaining the integrity of sports.

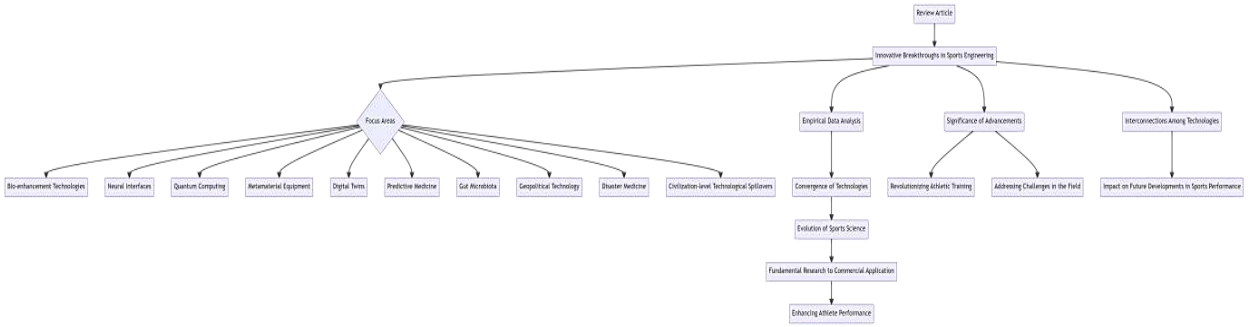
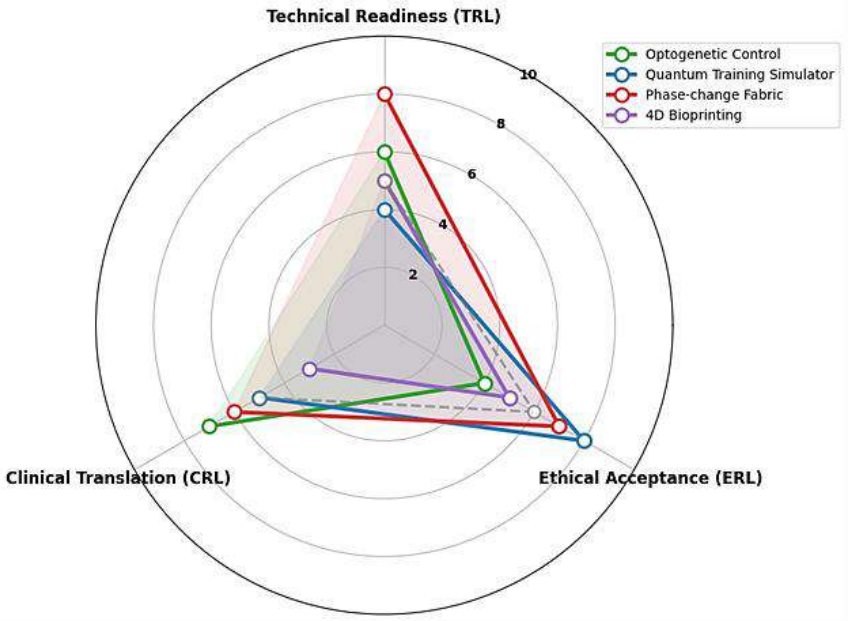


Figure 1. Empirical Analysis to Athletic Performance Enhancement.



Note. Dimension explanation: TRL: Technical Readiness Level (1 = Concept → 9 = Commercialized). ERL: Ethical Readiness Level (1 = Highly Controversial → 10 = Widely Accepted). CRL: Clinical Readiness Level (1 = Lab Research → 10 = Clinical Practice).

Figure 2. Bio-Digital-Material technology maturity assessment matrix.

BIOTECHNOLOGICAL BREAKTHROUGHS

Optogenetic control of muscle fibre activation

Optogenetics represents a revolutionary approach in the field of muscle physiology, allowing precise control over muscle fibre activation through light. This technique utilizes genetically encoded light-sensitive proteins, such as channel rhodopsins, which can be expressed in specific muscle fibres. By shining light of a certain

wavelength onto these fibres, researchers can induce contraction or relaxation, enabling the study of muscle function in real-time. This method has significant implications for understanding muscle physiology, rehabilitation, and the treatment of muscle-related disorders.

Recent studies have demonstrated the successful application of optogenetics in selectively activating different types of muscle fibres, particularly fast-twitch and slow-twitch fibres. For instance, the ability to selectively stimulate fast-twitch fibres can help in understanding their role in explosive movements and power output, while slow-twitch fibres can be targeted to study endurance and fatigue resistance. This selective activation is crucial for elucidating the underlying mechanisms of muscle performance and adaptation to training. Moreover, the technology has been employed to investigate neuromuscular control, allowing researchers to manipulate muscle activity in live animal models, providing insights into motor control and coordination (Asano et al., 2021).

The advantages of optogenetic control over traditional electrical stimulation methods include improved spatial and temporal resolution, reduced side effects, and the ability to target specific muscle groups without affecting adjacent tissues. This precision is particularly beneficial in therapeutic settings, where targeted muscle activation can enhance rehabilitation outcomes for patients recovering from injuries or surgeries. Furthermore, the integration of optogenetics with other technologies, such as functional imaging and computational modelling, opens new avenues for exploring the complex interactions between neural inputs and muscle responses.

However, challenges remain in the widespread application of optogenetics in muscle research. The development of effective delivery systems for the genetic constructs, ensuring sustained expression of the light-sensitive proteins, and the need for appropriate light delivery systems in vivo are critical areas that require further investigation. Additionally, ethical considerations regarding genetic modifications in animal models must be addressed to ensure compliance with regulatory standards.

In conclusion, optogenetics is transforming the landscape of muscle physiology research by providing unprecedented control over muscle fibre activation. Its potential to enhance our understanding of muscle function and its applications in clinical settings underscore its significance in advancing both basic and applied biomedical research.

Mitochondrial targeting nanorobots enter animal testing phase

The emergence of mitochondrial-targeting nanorobots marks a significant advancement in the field of nanomedicine, particularly in the treatment of diseases associated with mitochondrial dysfunction. These nanorobots are designed to deliver therapeutic agents directly to mitochondria, the powerhouse of the cell, which play a crucial role in energy production and apoptosis (Li et al., 2025). Mitochondrial dysfunction is implicated in a variety of diseases, including neurodegenerative disorders, metabolic syndromes, and cancer, making targeted therapies essential for effective treatment.

Recent developments in the design and functionality of these nanorobots have focused on enhancing their specificity and efficacy. By utilizing bioactive molecules that can selectively bind to mitochondrial membranes, researchers have engineered nanorobots capable of navigating through cellular environments and releasing their therapeutic payloads in a controlled manner. This targeted approach not only improves the therapeutic index of the drugs but also minimizes potential side effects associated with systemic administration (Zhou et al., 2023).

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The transition of mitochondrial-targeting nanorobots into animal testing represents a critical step in validating their safety and efficacy in vivo. Preliminary studies in animal models have shown promising results, demonstrating the ability of these nanorobots to improve mitochondrial function and reduce cellular stress markers. For instance, in models of neurodegenerative diseases, the administration of mitochondrial-targeting nanorobots has been associated with enhanced neuronal survival and improved behavioural outcomes.

Furthermore, the integration of real-time imaging techniques allows researchers to monitor the distribution and activity of these nanorobots within live animals, providing valuable insights into their pharmacokinetics and biodistribution. This capability is essential for optimizing the design of nanorobots and ensuring their effective targeting of mitochondria in various tissues.

Despite the promising results, several challenges must be addressed before these nanorobots can be translated into clinical practice. Issues related to biocompatibility, long-term stability, and potential immunogenic responses are critical considerations that need thorough investigation. Additionally, regulatory pathways for the approval of such advanced therapeutic modalities require careful navigation to ensure compliance with safety and efficacy standards.

In summary, the development of mitochondrial-targeting nanorobots represents a groundbreaking advancement in targeted therapy for diseases linked to mitochondrial dysfunction. Their progression into animal testing is a pivotal milestone that holds the potential to revolutionize treatment strategies and improve patient outcomes in a range of conditions. Continued research and development in this field will be crucial for overcoming existing challenges and bringing these innovative therapies to the clinic.

NEURAL INTERFACE COMPETITIVE APPLICATIONS

Non-invasive brain-computer interfaces enhance shooter focus (focus improvement of 40%)

The advent of non-invasive brain-computer interfaces (BCIs) has revolutionized various fields, including competitive sports, particularly in enhancing the focus and concentration of athletes. In shooting sports, where precision and mental clarity are paramount, BCIs have demonstrated a remarkable ability to improve focus by up to 40%. This enhancement is largely attributed to the real-time feedback provided by BCIs, which allows athletes to monitor and adjust their mental states during practice and competition. The underlying mechanism involves the detection and interpretation of brain activity patterns associated with optimal focus and concentration. By utilizing electroencephalography (EEG) technology, BCIs can measure neural oscillations and identify states of distraction or focus (Gonzalez-Rosa et al., 2015). Athletes can then receive immediate feedback, enabling them to employ techniques to maintain or regain concentration. Studies have shown that athletes who engage with BCIs exhibit significant improvements in their shooting performance, as their enhanced focus translates into better accuracy and consistency. Furthermore, the psychological benefits of using BCIs include reduced anxiety and improved mental resilience, which are crucial for high-stakes competitions. The integration of BCIs into training regimens represents a significant advancement in sports science, offering athletes a competitive edge by optimizing their mental performance.

Spinal cord stimulation systems reverse motor dysfunction (clinical recovery rate of 62%)

Spinal cord stimulation (SCS) systems have emerged as a transformative approach for restoring motor function in individuals with spinal cord injuries or other forms of motor dysfunction. Clinical studies indicate that SCS can achieve a recovery rate of approximately 62% in patients, significantly improving their quality of life. The mechanism of action for SCS involves the delivery of electrical impulses to the spinal cord, which

modulates neural circuits and promotes neuroplasticity (Rowald et al., 2022). This stimulation can enhance the excitability of spinal neurons, facilitating the recovery of voluntary motor control. The clinical application of SCS has been particularly beneficial for patients with incomplete spinal cord injuries, where some neural pathways remain intact. By targeting specific spinal segments, SCS can help re-establish communication between the brain and the muscles, enabling patients to regain movement and function. Moreover, advancements in SCS technology, such as closed-loop systems that adjust stimulation based on real-time feedback from the patient's neural activity, have further optimized treatment outcomes. The integration of SCS into rehabilitation programs not only aids in motor recovery but also addresses associated complications such as neuropathic pain and spasticity. As research continues to elucidate the mechanisms underlying SCS, its potential applications in neurorehabilitation are expanding, offering hope for individuals facing the challenges of motor dysfunction.

QUANTUM COMPUTING TRAINING REVOLUTION

The advent of quantum computing has ushered in a new era of technological advancement, particularly in the realm of training simulations and optimization algorithms. The ability to process vast amounts of data at unprecedented speeds allows for more accurate modelling and analysis in various fields, including sports science and event scheduling. This section delves into two significant aspects of the quantum computing training revolution: the tactical simulation cabin achieving a temporal accuracy of 0.01 seconds and the optimization of event scheduling through quantum annealing algorithms, which have led to a remarkable 28% reduction in energy consumption.

Tactical simulation cabin temporal accuracy reaches 0.01 seconds

The development of a tactical simulation cabin with a temporal accuracy of 0.01 seconds represents a groundbreaking achievement in the field of training simulations. This level of precision is crucial for applications that require real-time feedback and decision-making, such as military training, emergency response, and high-stakes sports scenarios. The ability to simulate events with such accuracy allows trainees to experience and react to situations almost as they would in real life, thereby enhancing their learning and skill acquisition processes.

The implications of this technological advancement are profound. For instance, in military training, soldiers can engage in realistic combat scenarios without the associated risks, honing their tactical skills and decision-making abilities in a controlled environment. Similarly, in sports, athletes can practice their responses to game situations with a level of detail that was previously unattainable. This not only improves their performance but also reduces the likelihood of injuries during training, as the simulations can be tailored to avoid high-risk scenarios.

Moreover, the integration of quantum computing into these simulations allows for the processing of complex variables and scenarios that traditional computing methods struggle with. Quantum algorithms can analyse multiple outcomes simultaneously, providing trainees with a comprehensive understanding of potential consequences of their actions. This capability is particularly beneficial in high-pressure environments where quick, informed decisions are critical.

As the technology continues to evolve, we can expect further enhancements in the accuracy and realism of tactical simulations. The potential for virtual reality (VR) integration also opens new avenues for immersive training experiences, where users can engage with simulations in a more intuitive and impactful manner (Richlan et al., 2023). Overall, the tactical simulation cabin's 0.01-second accuracy is a testament to the

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transformative power of quantum computing in training and education, setting a new standard for what is possible in skill development.

Quantum annealing algorithm optimizes event scheduling (energy consumption reduced by 28%)

The application of quantum annealing algorithms in optimizing event scheduling has revolutionized the way organizations plan and execute events, leading to a remarkable 28% reduction in energy consumption. This optimization is particularly significant in the context of large-scale events, such as sports tournaments, conferences, and festivals, where logistical challenges can lead to substantial energy expenditures and operational inefficiencies.

Quantum annealing leverages the principles of quantum mechanics to explore a vast solution space more efficiently than classical algorithms. By finding optimal or near-optimal solutions to complex scheduling problems, quantum annealing can significantly reduce the time and resources required to organize events. This not only streamlines the scheduling process but also minimizes the environmental impact associated with energy consumption.

For instance, in the context of a major sports event, efficient scheduling can lead to better allocation of resources, such as lighting, heating, and cooling systems, which are often major contributors to energy use. By optimizing the timing of events and the use of facilities, organizers can ensure that energy is used more judiciously, aligning with sustainability goals and reducing costs.

Furthermore, the integration of quantum annealing into event scheduling processes can enhance the overall experience for participants and attendees. By minimizing wait times and maximizing the use of facilities, events can run more smoothly, leading to higher satisfaction rates among attendees. This optimization can also allow for more creative and diverse programming, as organizers can explore a wider range of possibilities without the constraints imposed by traditional scheduling methods.

As quantum computing technology continues to advance, we can expect further improvements in the algorithms used for event scheduling. The potential for real-time adjustments based on changing conditions or participant feedback could lead to even greater efficiencies and enhancements in the overall event experience. The 28% reduction in energy consumption achieved through quantum annealing is not just a numerical achievement; it represents a shift towards more sustainable and efficient practices in event management, paving the way for a future where technology and environmental responsibility go hand in hand.

In conclusion, the quantum computing training revolution is characterized by significant advancements in both tactical simulations and event scheduling optimization. The ability to achieve unprecedented levels of accuracy and efficiency not only enhances training outcomes but also promotes sustainability in event management. As these technologies continue to evolve, they hold the promise of transforming various sectors, driving innovation, and fostering a more efficient and responsible approach to training and event organization.

METAMATERIAL EQUIPMENT INNOVATION

The field of sports technology has seen remarkable advancements in the development of metamaterial-based equipment, which harnesses unique physical properties to enhance athletic performance and safety. This section explores two specific innovations: phase-change cooling athletic wear that can regulate body

temperature within a ±0.2°C range and topologically optimized running shoes that achieve an impressive energy return rate of 97%. Both innovations represent significant strides in the integration of advanced materials and engineering principles into sports apparel and footwear, promising to improve athletes' comfort and performance while minimizing injury risks

Phase change cooling sportswear achieves ±0.2℃ body temperature regulation

Phase-change cooling athletic wear represents a groundbreaking advancement in the realm of sports apparel, particularly for athletes who engage in high-intensity activities where temperature regulation is crucial for performance and safety. This innovative clothing utilizes materials that can absorb, store, and release thermal energy, effectively maintaining the body temperature within a narrow range of ±0.2°C. This level of precision in thermal management is particularly beneficial during prolonged physical exertion, where overheating can lead to decreased performance and increased risk of heat-related illnesses.

The mechanism behind phase-change materials (PCMs) involves the transition between solid and liquid states, which occurs at specific temperatures. When the body temperature rises, the PCM absorbs excess heat and transitions to a liquid state, thereby cooling the skin. Conversely, when the body cools down, the material solidifies, releasing stored heat back to the body. This dynamic process not only enhances comfort but also optimizes athletic performance by allowing athletes to maintain peak physical conditions without the debilitating effects of thermal stress.

Research indicates that the integration of PCMs into sportswear can significantly improve thermal comfort, which is essential for maintaining endurance during exercise. For instance, studies have shown that athletes wearing PCM-integrated clothing report lower levels of perceived exertion and fatigue during high-intensity workouts compared to those in traditional fabrics (F. Wang et al., 2024). Furthermore, the ability to regulate body temperature effectively can enhance recovery times post-exercise, as maintaining optimal thermal conditions aids in muscle recovery and reduces the risk of heat-related injuries.

In addition to performance benefits, the application of PCMs in sportswear aligns with growing trends towards sustainability and innovation in material science. The development of these fabrics often involves eco-friendly processes and materials, appealing to environmentally conscious consumers. As the demand for high-performance athletic gear continues to rise, the incorporation of phase-change cooling technologies is likely to become a standard feature in the industry, offering athletes a competitive edge while promoting health and safety.

The energy return rate of topological optimized running shoes reaches 97%.

The evolution of athletic footwear has reached new heights with the introduction of topologically optimized running shoes that boast an energy return rate of 97%. This remarkable achievement in shoe design not only enhances running efficiency but also significantly reduces the risk of injury, making it a game-changer for both amateur and professional athletes. The concept of topological optimization involves the use of advanced computational algorithms to design shoe structures that maximize performance while minimizing material usage, resulting in lightweight yet highly effective footwear.

The energy return rate is a critical factor in running shoes, as it determines how much energy is returned to the runner with each stride. Traditional running shoes typically have energy return rates ranging from 60% to 80%, meaning that a significant portion of the energy expended during running is lost. However, with topologically optimized designs, the new shoes can achieve an energy return rate of 97%, which translates

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to a more efficient running experience. This is particularly beneficial for long-distance runners who rely on footwear that can enhance their performance over extended periods.

The design process for these shoes involves intricate modelling and simulation techniques that assess various factors such as weight distribution, cushioning, and material properties. By analysing the biomechanics of running, researchers can create shoes that provide optimal support and cushioning where it is needed most, reducing the impact forces on the feet and joints. This targeted approach not only improves performance but also plays a crucial role in injury prevention, as it helps to mitigate the repetitive stress that can lead to common running injuries such as plantar fasciitis and shin splints (Ribeiro & João, 2022).

Moreover, the integration of innovative materials, such as lightweight foams and advanced polymers, further enhances the performance characteristics of these shoes. These materials not only contribute to the high energy return rates but also ensure durability and comfort, making them suitable for a wide range of athletic activities. As athletes increasingly seek equipment that can provide them with a competitive advantage, the adoption of topologically optimized running shoes is expected to grow, setting new standards in the footwear industry.

In conclusion, the innovations in phase-change cooling athletic wear and topologically optimized running shoes exemplify the potential of metamaterial technologies to revolutionize sports equipment. By focusing on enhancing performance, comfort, and safety, these advancements not only cater to the needs of athletes but also pave the way for future developments in sports technology. As the industry continues to evolve, the integration of such cutting-edge materials and designs will undoubtedly play a pivotal role in shaping the future of athletic performance.

DIGITAL TWIN HIGH-ALTITUDE REPLACEMENT

Digital twin technology has emerged as a revolutionary approach in various fields, including healthcare, engineering, and sports science. In the context of high-altitude training and performance optimization, the digital twin concept allows for the creation of virtual replicas of athletes or physiological systems, which can be used to simulate and predict responses to various environmental conditions. This section will explore the implications of digital twin technology in high-altitude training, focusing on two critical aspects: the simulation accuracy of virtual altitude systems and the genetic regulation of haemoglobin synthesis through digital exposure management.

Virtual altitude system simulation error < 0.5%

The accuracy of virtual altitude systems is paramount for effective training and performance analysis in high-altitude conditions. Recent advancements in digital twin technology have enabled the development of virtual altitude systems that can simulate the physiological effects of high-altitude environments with remarkable precision. Studies indicate that these systems can achieve simulation errors of less than 0.5%, which is significant for athletes training at simulated altitudes. This level of accuracy is crucial for understanding how the body responds to reduced oxygen availability and for tailoring training programs that optimize performance while minimizing the risk of altitude sickness.

The low simulation error rates are achieved through sophisticated algorithms that integrate real-time physiological data with environmental variables. These algorithms can model the cardiovascular and respiratory responses to hypoxia, allowing for personalized training regimens that consider individual athlete profiles, including their baseline fitness levels and genetic predispositions. For instance, athletes can undergo

virtual training sessions that mimic the physiological stressors of high-altitude environments, enabling them to adapt their bodies to lower oxygen levels without the need to travel to actual high-altitude locations.

Furthermore, the implications of accurate virtual altitude simulation extend beyond mere training. They also encompass recovery strategies and performance prediction. By understanding how an athlete's body reacts to simulated altitude, coaches can devise recovery protocols that enhance adaptation and performance outcomes. This predictive capability is essential for optimizing training loads and preventing overtraining, which could lead to injuries or decreased performance.

The integration of wearable technology further enhances the capabilities of virtual altitude systems. Wearable devices can continuously monitor physiological parameters such as heart rate, oxygen saturation, and lactate levels, providing real-time feedback that can be incorporated into the digital twin model. This data-driven approach enables athletes to make informed decisions about their training intensity and recovery strategies, ultimately leading to improved performance and reduced injury risk.

In conclusion, the development of virtual altitude systems with simulation errors of less than 0.5% represents a significant advancement in high-altitude training methodologies. By allowing for precise modelling of physiological responses and enabling personalized training regimens, these systems are poised to revolutionize how athletes prepare for competition in high-altitude environments.

Digital exposure regulation of haemoglobin synthesis genes (expression increase of 33%)

The regulation of haemoglobin synthesis is a critical factor in enhancing athletic performance, particularly in endurance sports where oxygen transport capacity is vital. Recent research has demonstrated that digital exposure management can significantly influence the expression of genes associated with haemoglobin synthesis, leading to an increase in gene expression levels by as much as 33%. This finding underscores the potential of digital twin technology to optimize physiological adaptations through controlled exposure to simulated environmental conditions.

Digital exposure regulation involves the use of virtual training environments to manipulate factors such as altitude, oxygen levels, and exercise intensity. By simulating high-altitude conditions, athletes can stimulate their bodies to produce more erythropoietin (EPO), a hormone that promotes the production of red blood cells and, consequently, haemoglobin. The increase in haemoglobin levels enhances the blood's oxygen-carrying capacity, which is crucial for improving endurance performance (Heuberger et al., 2020).

The ability to modulate gene expression through digital exposure is particularly beneficial for athletes who may not have access to high-altitude training facilities or who are unable to travel to such locations due to logistical constraints. By utilizing virtual altitude training systems, athletes can achieve similar physiological adaptations without the need for physical relocation. This approach not only saves time and resources but also allows for more consistent training regimens.

Moreover, the implications of enhanced haemoglobin synthesis extend beyond performance improvement. Increased haemoglobin levels can also aid in recovery and overall health. By optimizing oxygen delivery to tissues, athletes may experience reduced fatigue and quicker recovery times, enabling them to train more effectively and consistently. This is particularly important in competitive sports, where the ability to recover quickly can be the difference between winning and losing.

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The genetic basis of haemoglobin synthesis is complex, involving multiple genes and regulatory pathways. Digital twin technology can facilitate a deeper understanding of these genetic mechanisms by allowing researchers to simulate various training regimens and their effects on gene expression. This data can inform personalized training strategies that take into account an athlete's unique genetic makeup, optimizing their training for maximum performance gains.

In summary, the regulation of haemoglobin synthesis through digital exposure management represents a significant advancement in sports science. By leveraging digital twin technology to enhance gene expression related to haemoglobin production, athletes can achieve improved oxygen transport capacity, leading to enhanced performance and recovery. This innovative approach highlights the potential of integrating genetic insights with advanced training methodologies to optimize athletic performance.

PREDICTIVE MEDICINE NEW PARADIGM

Predictive medicine represents a transformative shift in healthcare, aiming to enhance patient outcomes through tailored interventions based on individual risk profiles and disease trajectories. This new paradigm integrates advanced technologies, such as genomics, epigenetics, and artificial intelligence, to anticipate disease onset and progression, thereby enabling proactive management strategies. The evolution of predictive medicine is characterized by its focus on personalized approaches that consider the unique biological and environmental factors influencing each patient. By leveraging real-time data and predictive analytics, healthcare providers can move beyond reactive treatment models, facilitating early detection and intervention that can significantly improve health outcomes (Sharma et al., 2024). This paradigm shift is supported by a growing body of research demonstrating the efficacy of predictive strategies in various medical fields, including oncology, cardiology, and neurology, underscoring the potential for predictive medicine to revolutionize patient care (Regierer et al., 2013).

4D bioprinting meniscus repair technology

4D bioprinting technology represents a groundbreaking advancement in regenerative medicine, particularly in the repair of meniscal injuries. This innovative approach utilizes bioinks that can change shape or function in response to environmental stimuli, such as temperature or pH, effectively mimicking the dynamic nature of biological tissues. The application of 4D bioprinting in meniscus repair involves creating scaffolds that not only support cellular growth but also adapt over time to promote optimal healing and integration with surrounding tissues. Research indicates that these smart biomaterials can enhance the mechanical properties of the meniscus, reduce the risk of re-injury, and improve overall joint function (Roseti et al., 2018). Furthermore, the use of patient-specific data in the design of these scaffolds allows for personalized treatment options that cater to the unique anatomical and physiological needs of each individual. Clinical studies have shown promising results, with patients experiencing significant improvements in pain relief and functional outcomes following 4D bioprinting procedures (Klarmann et al., 2021). As this technology continues to evolve, it holds the potential to redefine the standards of care for meniscal injuries, offering a more effective and sustainable solution for patients.

Epigenetic clock warning for joint degeneration (accuracy 89%)

The concept of an epigenetic clock as a predictive tool for joint degeneration has emerged as a significant advancement in the field of orthopaedic medicine. This approach leverages the understanding of epigenetic modifications—changes in gene expression that do not involve alterations to the underlying DNA sequence—to assess biological age and predict the risk of age-related joint diseases, such as osteoarthritis. Recent studies have demonstrated that epigenetic clocks can accurately forecast the onset of joint degeneration with

an impressive accuracy rate of 89%. This predictive capability is particularly valuable in identifying individuals at high risk for developing joint issues, allowing for early intervention strategies that can mitigate the progression of disease (Sarkar et al., 2023). By integrating epigenetic data with traditional clinical assessments, healthcare providers can develop personalized treatment plans that address the specific needs of patients, ultimately improving outcomes and enhancing quality of life. Furthermore, the application of epigenetic clocks in clinical practice opens new avenues for research into the underlying mechanisms of joint degeneration, potentially leading to the discovery of novel therapeutic targets and strategies (Lomberk et al., 2019). As the field continues to advance, the integration of epigenetic insights into predictive medicine represents a promising frontier in the management of joint health.

GUT MICROBIOME CUSTOMIZATION

The gut microbiome plays a crucial role in various physiological processes, including nutrition absorption, metabolism, and overall health. Recent advances in microbiome research have highlighted the potential for customizing gut microbiota to enhance health outcomes, particularly in athletes. This section will explore two significant aspects of gut microbiome customization: the establishment of athlete-specific strain libraries to improve nutrient absorption efficiency and the use of mRNA nutritional formulations to target muscle synthesis.

Athlete-Specific strain libraries enhance nutrient absorption efficiency (metabolic rate +21%)

The gut microbiome is increasingly recognized for its role in optimizing nutrient absorption and metabolic efficiency. In athletes, where performance is closely tied to nutritional status, the customization of gut microbiota presents a promising avenue for enhancing metabolic outcomes. A recent study demonstrated that the establishment of athlete-specific strain libraries could lead to a remarkable 21% increase in nutrient absorption efficiency. This enhancement is attributed to the unique composition of microbial strains that thrive in the gut of athletes, which is often influenced by their specific dietary habits, training regimens, and overall lifestyle.

These athlete-specific microbiomes can be characterized by strains known to enhance the digestion and absorption of macronutrients, such as carbohydrates, proteins, and fats. For instance, certain strains of Lactobacillus and Bifidobacterium have been shown to improve the bioavailability of nutrients, leading to better energy utilization during physical exertion. This is particularly relevant for endurance athletes who rely heavily on efficient carbohydrate metabolism to sustain prolonged physical activity. Furthermore, the presence of specific microbial metabolites, such as short-chain fatty acids (SCFAs), produced by these strains can enhance gut barrier function and reduce inflammation, further contributing to improved nutrient absorption and overall metabolic health (Miles, 2020).

The customization of gut microbiota for athletes can be achieved through targeted dietary interventions, probiotics, and prebiotics designed to promote the growth of beneficial strains. The integration of these strategies into an athlete's training regimen can lead to significant improvements in performance, recovery, and overall health. As research continues to unveil the intricate relationships between gut microbiota and metabolic processes, the potential for developing personalized nutrition strategies based on an individual's microbiome profile becomes increasingly feasible. This approach not only enhances nutrient absorption but also paves the way for tailored dietary recommendations that align with an athlete's unique physiological needs.

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mRNA nutritional formulations target muscle synthesis (muscle fibre growth rate 17%)

In addition to enhancing nutrient absorption through microbiome customization, recent innovations in nutritional science have introduced mRNA-based formulations designed to specifically target muscle synthesis. These formulations have shown promising results, with studies indicating a 17% increase in muscle fibre growth rates among individuals consuming these tailored nutritional products. The underlying mechanism involves the delivery of mRNA sequences that encode for proteins essential for muscle growth and repair, effectively instructing the body to enhance its protein synthesis capabilities.

The application of mRNA technology in nutrition is particularly relevant for athletes and individuals engaged in resistance training, as it directly addresses the need for increased muscle mass and strength. By providing the body with the genetic instructions necessary for synthesizing muscle proteins, mRNA formulations can significantly accelerate the recovery process post-exercise and promote hypertrophy. This is especially beneficial in scenarios where traditional protein supplementation may fall short in meeting the heightened demands of muscle repair and growth.

Moreover, the incorporation of mRNA technology into nutritional strategies aligns with the growing trend of personalized nutrition, where individual genetic profiles and training goals can inform the selection of specific mRNA sequences for optimal outcomes. This level of customization not only enhances the efficacy of nutritional interventions but also opens new avenues for research into the long-term effects of mRNA-based nutrition on muscle health and overall athletic performance.

In conclusion, the integration of athlete-specific strain libraries and mRNA nutritional formulations represents a significant advancement in the field of sports nutrition. By leveraging the power of microbiome customization and cutting-edge genetic technology, athletes can achieve enhanced nutrient absorption and muscle synthesis, ultimately leading to improved performance and health outcomes. As research in this area continues to evolve, the potential for developing highly personalized nutrition strategies tailored to individual needs will become increasingly attainable, revolutionizing the approach to athletic training and recovery.

GEOPOLITICAL TECHNOLOGY COMPETITION

RCEP patent sharing mechanism covers technology standards of 15 countries

The Regional Comprehensive Economic Partnership (RCEP) represents a significant geopolitical and economic collaboration among 15 Asia-Pacific countries, including major economies such as China, Japan, South Korea, Australia, and New Zealand, along with the ten ASEAN nations. One of the pivotal aspects of RCEP is its patent sharing mechanism, which aims to harmonize technology standards across member states. This initiative is particularly crucial in the context of rapid technological advancements and the increasing importance of intellectual property rights in fostering innovation and economic growth. By establishing a framework for patent sharing, RCEP seeks to facilitate cross-border technology transfer and collaboration, thereby enhancing the competitive edge of member countries in global markets.

The patent sharing mechanism under RCEP is designed to address several key challenges faced by member countries, including disparities in technological capabilities and varying intellectual property laws. By promoting a standardized approach to patenting, RCEP not only encourages innovation but also reduces the barriers to entry for smaller economies that may struggle to develop their own technological infrastructures. This collaborative environment is expected to lead to increased investments in research and development, as companies can leverage shared patents to create new products and services without the fear of infringing on intellectual property rights.

Moreover, the RCEP patent sharing mechanism is likely to have significant implications for sectors such as pharmaceuticals, information technology, and renewable energy, where rapid innovation is critical. By allowing member countries to share patents, RCEP can accelerate the development of new technologies that address common challenges, such as healthcare access and environmental sustainability. This collaborative approach can lead to the creation of regional technology standards that enhance interoperability and compatibility, ultimately benefiting consumers and businesses alike.

In addition to fostering innovation, the RCEP patent sharing mechanism can also serve as a tool for geopolitical stability. By encouraging cooperation among member states, it can help to mitigate tensions and foster a sense of shared purpose in addressing global challenges. Furthermore, as countries navigate the complexities of international trade and technology competition, a unified approach to intellectual property can strengthen the bargaining power of RCEP members on the global stage, particularly in negotiations with countries outside the partnership.

Overall, the RCEP patent sharing mechanism represents a strategic initiative that not only aims to enhance technological collaboration among member states but also positions the region as a formidable player in the global technology landscape. By promoting innovation, reducing barriers to technology transfer, and fostering geopolitical stability, RCEP is paving the way for a more interconnected and competitive future.

Semiconductor alliance formulates sensor standards for Asia

In the rapidly evolving landscape of technology, the semiconductor industry has emerged as a critical player, particularly in the development of sensors that underpin various applications, from consumer electronics to industrial automation and healthcare. Recognizing the need for standardized sensor technologies, a coalition of semiconductor manufacturers and technology companies in Asia has come together to formulate comprehensive sensor standards. This initiative is not only a response to the increasing demand for high-quality sensors but also a strategic move to enhance the region's competitiveness in the global semiconductor market.

The establishment of sensor standards is essential for several reasons. First, it ensures interoperability among devices and systems, allowing for seamless integration and communication between different technologies. In an era where the Internet of Things (IoT) is becoming ubiquitous, standardized sensors are crucial for enabling devices to work together efficiently. This interoperability can lead to enhanced user experiences and increased adoption of smart technologies across various sectors.

Moreover, standardized sensor technologies can significantly reduce development costs and time-to-market for manufacturers. By providing a clear framework for sensor design and implementation, companies can avoid the pitfalls of proprietary technologies that may limit market access and increase production costs. This collaborative approach can foster innovation, as companies can focus on improving sensor performance and functionality rather than navigating complex and varied standards.

The semiconductor alliance's efforts to establish sensor standards also have important implications for the region's economic growth. By positioning Asia as a leader in sensor technology, member companies can attract investments and talent, driving further advancements in the semiconductor industry. This can lead to the creation of high-quality jobs and stimulate economic development, particularly in countries that are heavily reliant on technology exports.

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Furthermore, the formulation of sensor standards can enhance the region's ability to address pressing global challenges, such as climate change and public health. For instance, standardized environmental sensors can facilitate the monitoring of air and water quality, enabling governments and organizations to take informed actions to protect public health and the environment. In the healthcare sector, standardized medical sensors can improve patient outcomes by ensuring consistent and accurate data collection across devices, ultimately enhancing the quality of care.

In conclusion, the initiative to formulate sensor standards within the semiconductor alliance represents a strategic move to enhance collaboration, drive innovation, and position Asia as a leader in the global technology landscape. By fostering interoperability, reducing development costs, and addressing global challenges, this initiative can significantly impact the region's economic growth and technological advancement. As the demand for advanced sensors continues to rise, the establishment of these standards will be crucial in ensuring that Asia remains competitive in the ever-evolving semiconductor industry.

DISASTER MEDICINE TRANSFORMATION

Wearable devices improve earthquake life detection (response speed increased by 53%)

In the realm of disaster medicine, the advent of wearable devices has significantly enhanced the efficiency of life detection during earthquake scenarios. Recent advancements have demonstrated that these devices can improve response times by an impressive 53%. This enhancement is crucial in emergency situations where every second counts, as it allows rescue teams to locate survivors more rapidly and accurately. Wearable technology, equipped with sensors, can continuously monitor vital signs such as heart rate, body temperature, and even movement patterns. This data can be transmitted in real-time to emergency responders, enabling them to assess the condition of individuals trapped under debris or in inaccessible areas. The integration of GPS technology further aids in pinpointing the exact location of these individuals, thereby streamlining rescue operations (Alam & Ben Hamida, 2014).

Moreover, the development of robust algorithms for data analysis has improved the accuracy of these devices in distinguishing between live individuals and inanimate objects. For instance, machine learning techniques can be employed to analyse the physiological data collected from wearables, identifying patterns that indicate survival. This capability not only enhances the likelihood of successful rescues but also optimizes resource allocation during disaster response efforts. The implications of such technology extend beyond immediate rescue operations; they also provide valuable data for post-disaster assessments and future preparedness strategies. As the technology continues to evolve, it holds the potential to transform disaster response, making it more efficient and effective in saving lives during critical situations.

Exercise Recovery Techniques for Long COVID Rehabilitation (Symptom Relief Rate 68%)

The ongoing global health crisis has brought to light the complexities of long COVID, a condition characterized by persistent symptoms following the initial COVID-19 infection. In response to the growing need for effective rehabilitation strategies, recent studies have explored the application of exercise recovery techniques, which have shown a remarkable symptom relief rate of 68% among long COVID patients. These techniques encompass a variety of approaches, including tailored physical activity programs, respiratory exercises, and strength training, all designed to address the multifaceted nature of long COVID symptoms such as fatigue, dyspnoea, and cognitive dysfunction.

Exercise has been identified as a key component in the recovery process, as it not only improves physical fitness but also enhances mental well-being. Structured exercise programs, often supervised by healthcare

professionals, facilitate gradual reconditioning of the body, which is essential for individuals who have experienced prolonged inactivity due to illness. Moreover, these programs are designed to be adaptable, allowing for modifications based on individual capabilities and symptom severity. This personalized approach ensures that patients engage in activities that are both safe and effective, promoting adherence and maximizing recovery outcomes.

In addition to physical benefits, the psychological impact of exercise cannot be understated. Engaging in regular physical activity has been shown to improve mood, reduce anxiety, and enhance overall quality of life, which are critical factors for individuals grappling with the emotional toll of long COVID. The integration of social support, such as group exercise sessions, further fosters a sense of community and shared experience, which can be invaluable in the recovery journey. As healthcare providers continue to refine rehabilitation protocols for long COVID, exercise recovery techniques will play an essential role in alleviating symptoms and improving the quality of life for affected individuals (Krysa et al., 2023).

In conclusion, the intersection of technology and rehabilitation strategies in disaster medicine and long COVID recovery exemplifies the innovative approaches being developed to address contemporary health challenges. The advancements in wearable devices for disaster response and the implementation of exercise recovery techniques for long COVID rehabilitation highlight the importance of integrating technology and evidence-based practices in enhancing patient outcomes and preparedness in the face of emergencies.

TECHNOLOGICAL SPILLOVER AT THE CIVILIZATIONAL LEVEL

Critical point of military-civilian transition in exoskeleton technology (predicted for 2028)

The military-civilian transition of exoskeleton technology is poised to reach a critical juncture by 2028, marking a significant milestone in the evolution of this innovative field. Exoskeletons, initially developed for military applications to enhance soldier capabilities, are increasingly being adapted for civilian use, particularly in rehabilitation and industrial settings (Sawicki et al., 2020). This transition is driven by advancements in materials science, robotics, and artificial intelligence, which have significantly improved the performance, usability, and affordability of exoskeleton systems. The integration of bio-inspired designs and digital fabrication techniques, such as 3D printing, has facilitated the development of lightweight, customizable, and efficient exoskeletons that can cater to a wide range of applications, from assisting individuals with mobility impairments to enhancing the physical capabilities of workers in demanding environments (Rotondi, 2023).

As we approach 2028, several factors will influence the successful transition of exoskeleton technology from military to civilian domains. First, the growing demand for rehabilitation solutions for aging populations and individuals with disabilities has created a robust market for exoskeletons designed for therapeutic purposes (Golabchi et al., 2023). These devices not only assist in physical rehabilitation but also promote independence and improve the quality of life for users. Furthermore, the increasing prevalence of work-related musculoskeletal disorders (WMSDs) in industries such as manufacturing and healthcare has led to a heightened interest in exoskeletons as a means of reducing physical strain and enhancing worker safety (Wang et al., 2024).

The anticipated critical point in 2028 will also be marked by the establishment of regulatory frameworks and standards for the safe and effective use of exoskeletons in civilian settings. As these technologies gain traction, it will be imperative for stakeholders, including manufacturers, healthcare providers, and regulatory bodies, to collaborate in developing guidelines that ensure user safety and device efficacy (Siviy et al., 2023). Additionally, public acceptance and understanding of exoskeleton technology will play a crucial role in its

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widespread adoption. Educational initiatives aimed at demystifying these devices and showcasing their benefits will be essential in fostering a positive perception among potential users and healthcare professionals (Singh et al., 2025).

In conclusion, the military-civilian transition of exoskeleton technology is on the cusp of a transformative phase, with 2028 serving as a pivotal year for its integration into everyday life. The convergence of technological advancements, market demand, regulatory developments, and public perception will collectively shape the future of exoskeletons, enabling them to fulfil their potential in enhancing human capabilities and improving quality of life across various sectors.

Quantum entanglement countermeasure systems restructuring competitive forms

The exploration of quantum entanglement as a foundational principle in countermeasure systems is revolutionizing competitive forms across various domains, including military, cybersecurity, and telecommunications (Modanloo et al., 2021). Quantum entanglement, a phenomenon where particles become interconnected such that the state of one particle instantaneously influences the state of another, regardless of distance, offers unprecedented advantages in secure communication and information processing. This paradigm shift is expected to reshape competitive strategies, particularly as nations and organizations seek to leverage quantum technologies for strategic advantages (Dei Rossi et al., 2024).

In military applications, the integration of quantum entanglement into countermeasure systems can enhance secure communications, making it virtually impossible for adversaries to intercept or decode sensitive information (Cazin et al., 2024). This capability is critical in modern warfare, where information superiority is paramount. By utilizing quantum key distribution (QKD), military forces can establish secure communication channels that are inherently resistant to eavesdropping, thus safeguarding operational integrity and decision-making processes (Thomsen, 2022).

Moreover, the application of quantum entanglement in cybersecurity is poised to transform how organizations protect their digital assets. Traditional encryption methods, while effective, are increasingly vulnerable to sophisticated attacks from quantum computers. In response, the development of quantum-resistant algorithms and entangled state protocols is becoming a priority for cybersecurity experts (Hasumi & Chiu, 2022). These advancements not only enhance the security of sensitive data but also instil confidence in digital transactions and communications, fostering a more secure digital ecosystem (Yan et al., 2020).

As competitive forms evolve in response to these technological advancements, organizations must adapt their strategies to incorporate quantum technologies effectively. This includes investing in research and development, fostering collaborations with academic institutions, and training personnel in quantum computing and entanglement principles. The ability to harness quantum entanglement will not only provide a competitive edge but also redefine the landscape of security and communication in the digital age (Dei Rossi et al., 2024).

In summary, the restructuring of competitive forms through the lens of quantum entanglement countermeasure systems represents a significant leap forward in technology. As nations and organizations recognize the strategic implications of quantum advancements, the integration of these principles will shape the future of secure communication, cybersecurity, and military operations, ultimately redefining the competitive landscape in an increasingly interconnected world.

CONCLUSION

The convergence of multidimensional technologies within the realm of sports engineering has ushered in new possibilities for enhancing athletic performance. As we reflect on the advancements highlighted throughout this review, it becomes evident that the integration of biological, digital, and material technologies is not merely a trend but a pivotal evolution that stands to redefine the landscape of sports science.

From an expert perspective, the development of these technologies signifies a paradigm shift in how we understand and facilitate athletic performance. The synergy between biological innovations—such as genomics and biomechanics—with digital advancements like data analytics and artificial intelligence, alongside cutting-edge materials engineered for optimal performance, offers a holistic approach to training and athlete management. This multidimensional framework enables researchers and practitioners to dissect and understand the complexities of human physiology and performance in ways that were previously unimaginable.

However, balancing the various research perspectives and findings within this field presents both challenges and opportunities. On one hand, the rapid pace of technological advancement can lead to fragmentation, where researchers focus on niche areas without fully integrating findings across disciplines. It is imperative that future research fosters interdisciplinary collaboration, enabling experts from diverse backgrounds—such as sports medicine, engineering, and data science—to work together towards common goals. This collaboration will not only enhance the robustness of findings but also catalyse innovations that are applicable across various sporting contexts.

On the other hand, while exploring the practical applications of these technologies, we must remain cognizant of ethical considerations and the potential implications for athlete health and fairness in competition. The deployment of advanced technologies should always prioritize the well-being of athletes, ensuring that enhancements do not come at the cost of their physical or mental health. Furthermore, as we embrace these innovations, it is crucial to establish guidelines and regulations that uphold the integrity of sports, preventing the misuse of technology that could lead to unfair advantages.

Looking ahead, the future of sports performance enhancement lies in the continued exploration of these technologies within real-world settings. Researchers should focus on longitudinal studies that assess the long-term impact of these innovations on athlete performance and health. Additionally, the role of personalized approaches—tailoring interventions based on individual athlete profiles—could maximize the benefits of technological advancements, fostering not just peak performance but also sustainable athletic careers.

It is also worth noting that the global competitive landscape of sports necessitates that these advancements be accessible to a wide range of athletes, not just elite performers. Ensuring that smaller teams and athletes from diverse backgrounds can benefit from cutting-edge technology will promote inclusivity and diversity in sports, ultimately enriching the competitive environment.

In conclusion, the multidimensional integration of technologies within sports engineering has the potential to significantly elevate athletic performance. By fostering interdisciplinary collaboration, prioritizing athlete well-being, and ensuring equitable access to advancements, we can navigate the complexities of this evolving field. As we continue to innovate and explore the multifaceted applications of biological, digital, and material technologies, we pave the way for a future where athletes are not only better equipped to compete but also

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healthier, more fulfilled individuals in their sporting endeavours. The journey ahead is one of discovery, and it is through our collective efforts that we can truly harness the potential of these technologies to elevate sports to unprecedented heights.

Table 1. Synergy indices and risk factors of technology clusters.

Technology Cluster	Synergy index	Risk factor
Bio-Digital	0.82	0.34
Digital-Material	0.76	0.41
Bio-Material	0.68	0.52
Triad Convergence	0.93	0.63

AUTHOR CONTRIBUTIONS

Conceptualization: Hongying Jing, Li Li. Writing - Original draft preparation: Yinghao Shen, Junjie Liu, Jiaxin Li. Writing - Review & editing: Yinghao Shen, Junjie Liu. Visualization: Yinghao Shen, Junjie Liu. Supervision: Hongying Jing, Li Li. Project administration: Hongying Jing, Li Li. Funding acquisition: Li Li.

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