ORIGINAL ARTICLE

From virtual practice to real-world performance: A transfer-oriented adaptive VR and motion tracking framework for junior tennis training

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ABSTRACT

Advances in digital sports training have expanded opportunities to improve motor skill development among junior athletes. Virtual Reality (VR) combined with motion tracking technology provides immersive training environments and real-time biomechanical feedback that may enhance tennis performance. However, evidence regarding adaptive simulation-based VR systems for junior tennis athletes remains limited. This study aimed to examine the effectiveness of integrating adaptive VR and motion tracking technology in optimizing motor skills among junior tennis athletes. A quasi-experimental pre-test–post-test control group design was employed involving 60 junior tennis athletes aged 12–18 years from two tennis development centres in Bali, Indonesia. The experimental group (n = 30) received adaptive VR and motion tracking-based training integrated with conventional tennis practice, while the control group (n = 30) followed conventional training only. The intervention was conducted over twelve weeks with three training sessions per week. Motor performance was assessed through stroke accuracy, reaction time, movement coordination, and biomechanical consistency tests. Data were analysed using paired-sample t-tests, independent-sample t-tests, and multivariate analysis of variance (MANOVA) with a significance level of $p < .05$. The results showed that the experimental group achieved significantly greater improvements than the control group across all variables. Stroke accuracy increased by 24.8%, reaction time improved by 18.6%, movement coordination increased by 21.3%, and biomechanical consistency improved by 19.7%. MANOVA revealed a significant multivariate effect of the intervention on overall motor skill development (Wilks' $\lambda = 0.71$, $F(8, 108) = 5.84$, $p < .001$). These findings indicate that adaptive VR and motion tracking-based training effectively enhances motor skill acquisition among junior tennis athletes and can serve as an innovative, evidence-based complement to conventional tennis coaching programs.
Keywords: performance analysis; virtual reality; motion tracking; adaptive simulation; motor skills; tennis training; junior athletes.

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INTRODUCTION

The rapid advancement of digital technologies has significantly transformed contemporary sports training methodologies, creating new opportunities for enhancing athlete performance through technology-assisted learning environments. Among emerging technologies, Virtual Reality (VR) has received substantial attention because of its ability to create immersive, interactive, and realistic simulations that closely replicate competitive sporting situations. Unlike conventional training methods, VR enables athletes to repeatedly practice technical and tactical skills within controlled environments while receiving immediate feedback on performance execution. Recent studies have demonstrated that VR-based training contributes to improvements in motor learning, perceptual-cognitive skills, reaction speed, movement accuracy, and decision-making performance across various sports disciplines (Richlan et al., 2023; Witte et al., 2025; Cariati et al., 2025). Motor skill development is a fundamental determinant of athletic success in tennis. Tennis performance requires the integration of complex motor abilities, including hand-eye coordination, reaction time, movement efficiency, balance, spatial awareness, stroke accuracy, and biomechanical consistency. For junior athletes, the developmental phase between adolescence and early adulthood represents a critical period during which motor learning experiences significantly influence long-term performance outcomes. Consequently, training interventions that facilitate efficient motor learning and movement adaptation are particularly valuable for maximizing athletic potential during this stage of development (Tang, 2024).

Despite continuous improvements in coaching methodologies, traditional tennis training approaches remain constrained by several limitations. Coaches frequently rely on subjective visual observations when evaluating athletes' technical performance, which may reduce the accuracy of movement assessment and delay corrective feedback. Furthermore, conventional training environments often fail to provide standardized practice conditions and individualized learning experiences. These limitations may hinder motor skill acquisition and reduce training effectiveness, particularly among junior athletes who require frequent feedback and repetitive skill practice to achieve optimal performance development. Recent advances in motion tracking technology have introduced promising solutions for overcoming these challenges. Motion tracking systems enable the precise measurement of human movement through wearable inertial sensors, marker less tracking devices, depth cameras, and artificial intelligence-based biomechanical analysis. Such technologies provide objective information regarding movement trajectories, joint angles, velocity profiles, and technical execution patterns, allowing coaches to make evidence-based decisions regarding athlete development. Motion tracking has therefore become an increasingly important component of modern sport science and athlete monitoring systems (Suo et al., 2024).

The integration of motion tracking technology with immersive VR environments has further expanded the possibilities of technology-enhanced sports training. This integration enables real-time biomechanical feedback during skill execution, allowing athletes to immediately recognize and correct movement errors. In contrast to traditional video-based analysis, VR-motion tracking systems provide interactive feedback directly within the simulated training environment, thereby increasing athlete engagement and facilitating deeper motor learning processes. Research indicates that real-time feedback mechanisms contribute significantly to the development of movement efficiency and technical consistency in sports performance (Li et al., 2025). Another important advantage of VR-based training is its ability to strengthen perception-action coupling, which refers to the continuous interaction between environmental information and motor responses. In open-skill sports such as tennis, athletes must constantly adapt their movements according to rapidly changing game situations. Virtual environments can simulate these dynamic conditions while maintaining precise control over training variables. Consequently, athletes are able to practice decision-making, anticipation, and motor execution under realistic yet controlled circumstances that support effective skill transfer to actual competition settings (Witte et al., 2025).

A central theoretical issue in technology-enhanced sport training is whether skills acquired in virtual environments can transfer to real-world performance. In VR-based sport training, improvements within simulated environments do not necessarily guarantee equivalent gains in actual performance because transfer depends on the similarity of perceptual-motor demands, representativeness of practice conditions, meaningful feedback, and athletes' ability to recalibrate learned responses in physical environments (Gray, 2022; Witte et al., 2025). This challenge is particularly relevant in tennis, where performance requires continuous integration of perception, decision-making, and movement execution under dynamic conditions that cannot be fully replicated in VR. Therefore, adaptive progression and motion tracking may provide complementary mechanisms for strengthening transfer by progressively increasing perceptual-motor demands, delivering objective movement feedback, and enabling athletes to recalibrate simulated learning through on-court practice. Accordingly, the present study conceptualizes adaptive VR not merely as a technological training tool, but as a transfer-oriented learning ecosystem in which immersive simulation, real-time feedback, individualized progression, and physical practice interact to facilitate the transfer of perceptual-motor adaptations from virtual environments to real-world tennis performance.

Although previous studies have reported positive effects of VR interventions on sports performance, several important research gaps remain. First, most existing investigations have focused on general motor learning, rehabilitation, physical education, or recreational sports rather than competitive junior athletes. Second, many VR-based training programs employ static training scenarios that fail to adapt to individual athlete characteristics and performance levels. Such standardized approaches may limit training effectiveness because athletes possess diverse motor abilities, learning rates, and technical competencies that require personalized intervention strategies (Richlan et al., 2023). Adaptive simulation has recently emerged as an innovative approach for addressing these limitations. Adaptive simulation systems automatically modify task difficulty, movement complexity, stimulus presentation, ball trajectory, and response requirements according to real-time athlete performance. This approach is consistent with contemporary motor learning theories emphasizing individualized feedback, optimal challenge points, and progressive task adaptation as essential components of effective skill acquisition. However, empirical studies investigating the integration of adaptive simulation, VR, and motion tracking technologies within tennis training remain scarce, particularly among junior athletes.

Despite growing evidence of VR effectiveness in sports training, a critical conceptual gap remains in explaining how skills acquired in virtual environments transfer to real-world sport performance. Existing studies often emphasize immediate improvements in simulated tasks or isolated motor outcomes, while the mechanisms linking adaptive VR practice, individualized progression, and subsequent skill transfer remain insufficiently understood, particularly in junior tennis. The present study addresses this gap by integrating immersive VR, motion tracking, and performance-contingent adaptive simulation within a transfer-oriented training framework, in which real-time performance data regulate individualized task difficulty and on-court practice facilitates the recalibration of learned perceptual-motor responses. This framework positions skill transfer as the central mechanism connecting technology-assisted practice with real-world tennis performance and extends conventional VR training research beyond technological integration toward a theoretically grounded model of adaptive motor learning and performance transfer.

To address these gaps, the present study investigates the effectiveness of integrating Virtual Reality and motion tracking technologies through an adaptive simulation framework for optimizing motor skill development among junior tennis athletes. The proposed system combines immersive VR training, real-time biomechanical monitoring, and adaptive difficulty adjustment to create a personalized learning environment. The novelty of this study lies in the integration of three advanced technological components within a single training ecosystem and the comprehensive evaluation of multiple motor performance indicators. The findings are expected to contribute to the growing body of knowledge regarding technology-enhanced sports training and provide practical recommendations for coaches, sport scientists, and athlete development programs seeking innovative approaches to improving junior tennis performance.

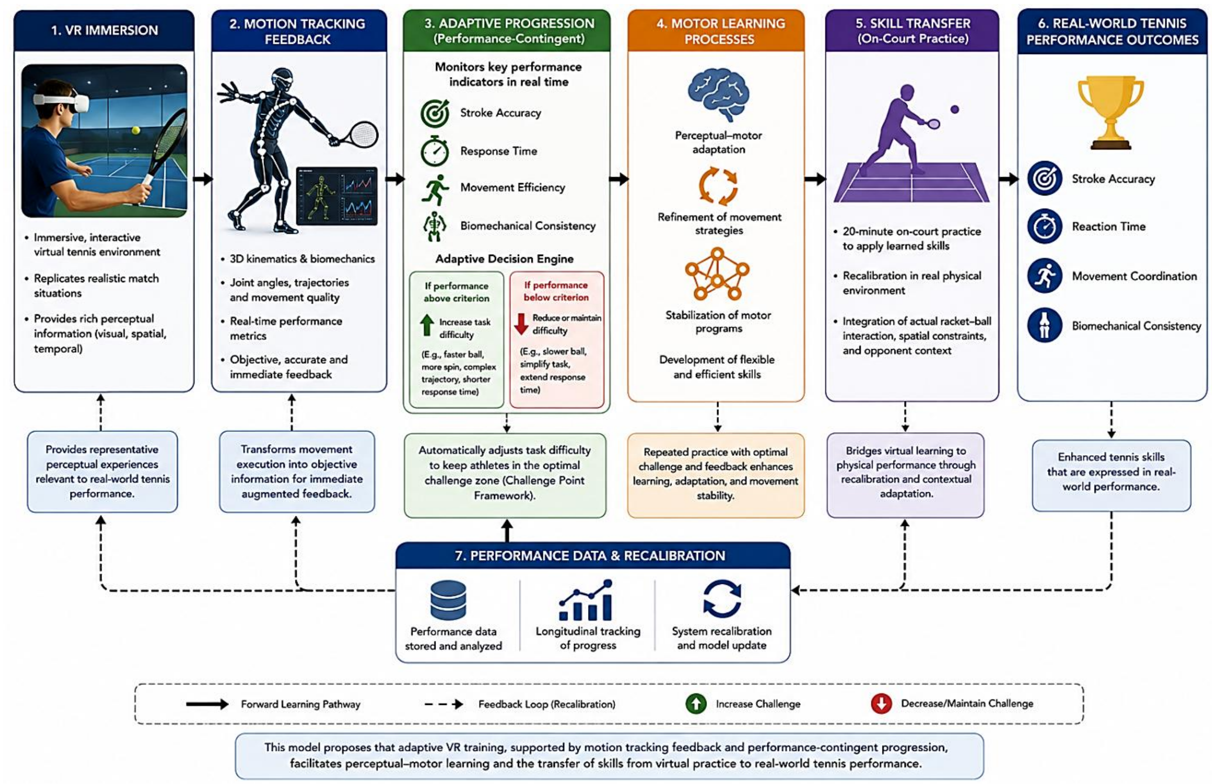

Figure 1. Performance-contingent adaptive VR training algorithm.

Based on these theoretical considerations, the present study proposes a transfer-oriented conceptual model in which adaptive VR functions as a dynamic learning ecosystem linking virtual practice to real-world tennis performance (Figure 2). VR immersion provides sport-specific perceptual experiences, motion tracking delivers objective feedback, and performance-contingent adaptation regulates individualized task difficulty. These processes promote perceptual-motor learning that is reinforced through on-court practice, enabling the transfer and recalibration of learned skills in the physical environment. Thus, the model positions transfer of learning as the central pathway through which adaptive VR may improve stroke accuracy, reaction time, movement coordination, and biomechanical consistency.

METHODS

Study design

A quasi-experimental pre-test–mid-test–post-test control group design was employed to examine the effects of adaptive VR and motion tracking training on junior tennis athletes' motor performance. Participants were allocated to an experimental group receiving adaptive VR-based training and a control group receiving conventional tennis training. Motor performance was assessed at baseline, 6 weeks, and 12 weeks using four primary outcomes: stroke accuracy, reaction time, movement coordination, and biomechanical consistency. The study focused on quantitative evaluation of changes over time and differences between groups.

Participants

A total of 60 junior tennis athletes aged 12–18 years participated in the study. Participants were recruited from two independent tennis development centres in Bali, Indonesia: Mandiri Tennis Development Center (MTDC), Singaraja (n = 30), and Bali Junior Tennis Academy (BJTA), Buleleng (n = 30). The larger multi-club sample was deliberately selected to improve external validity and enhance the generalizability of findings across different training environments (Hulteen et al., 2022). Eligibility criteria included: (a) minimum two years of competitive tennis experience; (b) active participation in regular club training programs; (c) absence of musculoskeletal injuries during the previous six months; and (d) parental consent for participants under 18 years old. Athletes with neurological disorders, current injuries, or previous experience using VR-based tennis training systems were excluded. Based on an a priori power analysis conducted using G*Power 3.1 (effect size = 0.30, α = 0.05, power = 0.80), a minimum sample size of 52 participants was required. Therefore, the recruitment of 60 athletes exceeded the minimum statistical requirement and reduced the risk of underpowered analyses (Faul et al., 2009).

The two participating tennis centres followed structured junior development programs with comparable training schedules and competitive objectives. Both centres provided regular technical, tactical, physical, and match-play training for junior athletes and maintained organized coaching programs throughout the study period. The experimental group was recruited from Mandiri Tennis Development Center (MTDC), while the control group was recruited from Bali Junior Tennis Academy (BJTA). To reduce contextual differences between groups, the study documented training frequency, session duration, coaching structure, and routine training content throughout the intervention. Both groups continued their regular tennis training at three sessions per week with comparable training volume, while the experimental group received the additional adaptive VR-motion tracking component. The same eligibility criteria, assessment schedule, outcome measures, and testing procedures were applied to both groups.

Intervention procedures

The intervention was conducted over 12 weeks to provide sufficient exposure for motor adaptation and skill acquisition. Previous motor learning research suggests that longer intervention periods improve the stability and retention of learned motor behaviours (Schmidt et al., 2019; Krakauer et al., 2023). Participants in the experimental group received adaptive VR-motion tracking training three times per week, with each session lasting 90 minutes. Sessions consisted of:

1. Dynamic warm-up (15 min).
2. Adaptive VR tennis simulation training (45 min).
3. On-court skill transfer practice (20 min).
4. Cool-down and performance feedback (10 min).

The control group followed conventional tennis training programs with identical training volume and frequency but without VR or motion tracking integration.

Adaptive VR and motion tracking system

The adaptive simulation engine used a performance-contingent progression system that continuously adjusted task difficulty based on four indicators: stroke accuracy, response time, movement efficiency, and biomechanical consistency. At each session, the system established an individualized baseline and compared real-time performance against predefined task-specific criteria. When performance remained above the target, task difficulty increased through faster ball velocity, greater spin, altered shot placement, higher movement complexity, or shorter response demands; when performance declined, task demands were reduced or maintained to stabilize movement execution. This continuous assessment–adjustment–recalibration cycle individualized each athlete's learning trajectory and maintained an optimal challenge level consistent with the Challenge Point Framework (Guadagnoli & Lee, 2004).

Following each VR session, athletes completed 20 minutes of on-court transfer practice to apply and recalibrate movement solutions developed in the virtual environment. This physical practice served as a critical bridge between simulated perceptual-motor learning and real-world tennis performance, enabling athletes to adapt learned responses to actual sensory, spatial, and biomechanical constraints. Thus, adaptive simulation functioned not only to progressively regulate VR task difficulty but also to prepare athletes for the transfer and contextualization of perceptual-motor skills in real tennis environments.

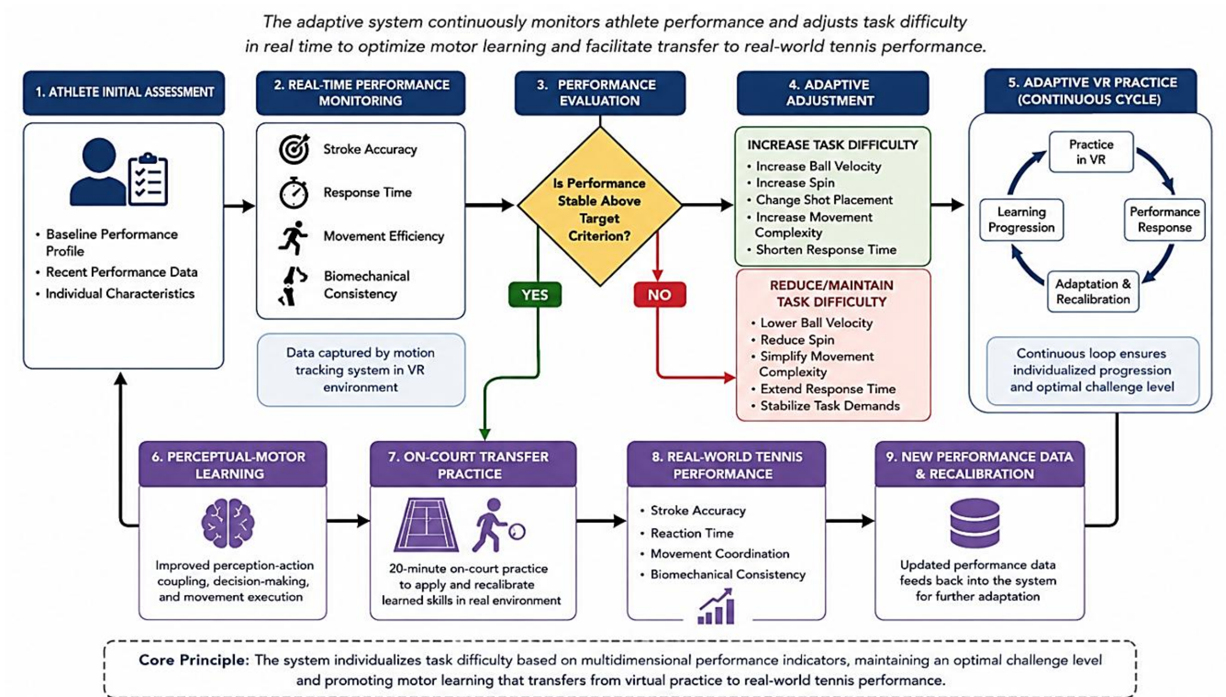

Figure 2. Transfer-oriented conceptual model of adaptive VR and motion tracking for tennis skill development.

Outcome measures

Stroke accuracy was assessed using a standardized target-based tennis test comprising 20 forehand and 20 backhand trials. Athletes performed strokes toward predefined target zones under standardized ball-feeding conditions. Each successful shot landing within the designated target zone received one point, whereas shots landing outside the target area received zero points. The final accuracy score was calculated as the percentage of successful shots out of the total number of trials. The same testing protocol, target dimensions, ball-feeding procedure, and court conditions were applied at baseline, mid-test, and post-test.

Motor skill performance was evaluated using four primary indicators:

Stroke accuracy
Forehand and backhand accuracy were assessed using a standardized target-based tennis skill test. Scores represented the percentage of successful shots landing within predefined target zones.

Reaction time
Reaction time was assessed using a tennis-specific computerized response task integrated into the VR environment. Participants responded to randomly presented visual stimuli representing incoming ball directions by initiating the corresponding movement response. Reaction time was recorded in milliseconds from stimulus presentation to the initiation of the predefined motor response. Multiple trials were administered under standardized conditions, and the mean response time across valid trials was used as the primary outcome. Invalid trials and technical errors were excluded according to predefined criteria.

Movement coordination
Movement coordination was assessed using a standardized tennis-specific agility and coordination protocol combining multidirectional footwork with stroke execution sequences. Participants completed a predefined sequence of movement and stroke tasks under standardized timing and spatial conditions. Performance was scored using a composite criterion incorporating task completion, movement accuracy, and execution consistency, with higher scores indicating more efficient and coordinated movement performance. The same sequence and scoring criteria were applied at baseline, mid-test, and post-test.

Biomechanical consistency
Biomechanical consistency was assessed using motion-tracking data obtained from the Azure Kinect DK and wearable inertial measurement units. The analysis focused on movement repeatability, joint angular variability, and stroke execution consistency across repeated trials. Lower variability in key kinematic parameters and higher repeatability of movement trajectories indicated greater biomechanical consistency. A composite biomechanical consistency score was calculated from standardized kinematic indicators, with higher scores representing greater movement stability and repeatability. Measurements were conducted at baseline (Week 0), midpoint (Week 6), and post-intervention (Week 12) using the same calibration and analysis procedures.

Reliability and validity procedures
To strengthen methodological transparency and reproducibility, test–retest reliability was assessed in a subsample of 15 athletes from the current study before the main outcome analysis. The Intraclass Correlation Coefficients (ICCs) ranged from .87 to .94, with coefficients of variation below 5%, indicating excellent measurement stability. The reliability assessment was conducted using the same standardized testing procedures, equipment, and measurement conditions as those used in the main study.

Content validity was established through expert review involving three sport scientists, two certified tennis coaches, and one biomechanical analyst. Construct validity was examined by comparing motion-tracking outputs with high-speed video analysis, which demonstrated strong agreement (r = .82 – .91). Because the reliability assessment was conducted using a subsample of the current participants, the reported ICC values represent reliability estimates obtained within the present study rather than coefficients derived from previous validation studies.

Data analysis
A two-way repeated-measures MANOVA was conducted as the primary analysis to examine the effects of group, time, and the group-by-time interaction across the four motor performance outcomes. This analysis

was used to determine whether changes from baseline to 6 and 12 weeks differed between the experimental and control groups. To account for potential baseline differences associated with the non-randomized group allocation, a follow-up MANCOVA was conducted using post-test scores as dependent variables, training group as the fixed factor, and corresponding baseline scores as covariates. Adjusted between-group differences were reported with 95% confidence intervals and partial eta squared (η^2). Statistical significance was set at $p < .05$.

Given the quasi-experimental design, findings were interpreted as evidence of effectiveness within the study context rather than definitive causal proof. Therefore, conclusions were framed cautiously to avoid overgeneralization beyond the sampled population and intervention setting, consistent with current recommendations for applied sport science research.

RESULTS

Participant characteristics

A total of 60 junior tennis athletes completed the study without dropouts, resulting in a retention rate of 100%. The experimental group (Mandiri Tennis Development Center, n = 30) and control group (Bali Junior Tennis Academy, n = 30) demonstrated comparable baseline characteristics. No significant differences were observed between groups regarding age, training experience, height, weight, or baseline motor performance indicators ($p > .05$).

Table 1. Participant and training characteristics of the experimental and control groups.

Variable	Experimental group (MTDC)	Control group (BJTA)
Sample size, n	30	30
Age range	12–18 years	12–18 years
Training frequency	3 sessions/week	3 sessions/week
Intervention duration	12 weeks	12 weeks
Session duration	90 min/session	90 min/session
Regular tennis training	Yes	Yes
Adaptive VR training	Yes	No
Motion tracking	Yes	No
On-court transfer practice	20 min/session	No
Tennis academy	MTDC	BJTA

Note. MTDC = Mandiri Tennis Development Center; BJTA = Bali Junior Tennis Academy.

Changes in stroke accuracy

The experimental group demonstrated substantial improvements in stroke accuracy throughout the intervention period. Mean accuracy scores increased from 68.43% at baseline to 85.41% at post-test, representing a 24.81% improvement. In contrast, the control group increased from 69.12% to 75.23% (8.84%). Repeated-measures analysis revealed a significant group × time interaction, $F(2, 116) = 18.64$, $p < .001$, $\eta p^2 = .243$.

Table 2. Changes in stroke accuracy (%).

Measurement	Experimental group	Control group
Pre-test	68.43 ± 6.12	69.12 ± 6.44
Mid-test	76.52 ± 5.81	72.18 ± 6.01
Post-test	85.41 ± 5.37	75.23 ± 5.96
Improvement (%)	+24.81	+8.84

Repeated-measures analysis revealed a significant group × time interaction effect ($F(2, 116) = 18.64$, $p < .001$, $\eta p^2 = .243$).

Changes in reaction time

Reaction time improved significantly among athletes exposed to adaptive VR and motion tracking training. The experimental group reduced mean reaction time from 0.542 s to 0.441 s, representing an 18.63% improvement, whereas the control group decreased from 0.538 s to 0.501 s (6.88%). The group × time interaction was statistically significant, $F(2, 116) = 15.91$, $p < .001$, $\eta p^2 = .215$.

Table 3. Changes in reaction time (seconds).

Measurement	Experimental group	Control group
Pre-test	0.542 ± 0.051	0.538 ± 0.048
Mid-test	0.487 ± 0.043	0.521 ± 0.045
Post-test	0.441 ± 0.038	0.501 ± 0.041
Improvement (%)	18.63	6.88

Statistical analysis indicated a significant group × time interaction ($F(2, 116) = 15.91$, $p < .001$, $\eta p^2 = .215$).

Changes in movement coordination

Movement coordination scores increased from 71.28 to 86.47 points in the experimental group, corresponding to a 21.31% improvement. The control group increased from 71.82 to 77.64 points (8.10%). The group × time interaction was statistically significant, $F(2, 116) = 17.23$, $p < .001$, $\eta p^2 = .229$.

Table 4. Changes in movement coordination scores.

Measurement	Experimental group	Control group
Pre-test	71.28 ± 5.92	71.82 ± 6.03
Mid-test	79.43 ± 5.17	74.61 ± 5.66
Post-test	86.47 ± 4.88	77.64 ± 5.34
Improvement (%)	+21.31	+8.10

The interaction effect between group and measurement time was statistically significant ($F(2, 116) = 17.23$, $p < .001$, $\eta p^2 = .229$).

Changes in biomechanical consistency

Biomechanical consistency scores increased from 72.13 to 86.34 points in the experimental group, representing a 19.70% improvement. The control group increased from 72.41 to 77.52 points (7.06%). A significant group × time interaction was observed, $F(2, 116) = 14.88$, $p < .001$, $\eta p^2 = .204$.

Table 5. Changes in biomechanical consistency scores.

Measurement	Experimental group	Control group
Pre-test	72.13 ± 5.46	72.41 ± 5.73
Mid-test	79.85 ± 4.98	74.83 ± 5.24
Post-test	86.34 ± 4.62	77.52 ± 5.11
Improvement (%)	+19.70	+7.06

A significant group × time interaction was observed ($F(2, 116) = 14.88$, $p < .001$, $\eta p^2 = .204$).

Multivariate analysis of motor skill development

To determine the overall effectiveness of the adaptive VR and motion tracking intervention, a repeated-measures MANOVA was conducted across all motor performance variables.

Table 6. MANOVA results for motor skill variables.

Effect	Wilks' λ	F(8, 108)	*p*	η²
Time	0.522	25.48	<.001	.478
Group	0.741	5.07	<.001	.259
Time × Group	0.709	5.84	<.001	.291

The MANOVA results demonstrated a statistically significant multivariate effect of the intervention on overall motor skill development (Wilks' $\lambda = 0.709$, $F(8, 108) = 5.84$, $p < .001$). The effect size indicated a moderate-to-large practical impact of the adaptive VR and motion tracking training program.

Adjusted multivariate analysis

To account for potential baseline differences arising from the non-randomized allocation of participants across two tennis academies, an adjusted multivariate analysis was conducted. MANCOVA was performed using post-test stroke accuracy, reaction time, movement coordination, and biomechanical consistency as dependent variables, with training group as the fixed factor and corresponding baseline scores as covariates. The adjusted analysis was used to determine whether the observed post-intervention differences between groups remained after accounting for baseline performance. Adjusted group effects, 95% confidence intervals, and partial eta squared were reported to improve the robustness and interpretability of the findings.

Summary of improvements across variables

The multivariate analysis demonstrated significant differences in motor performance outcomes between the experimental and control groups over the 12-week intervention period. The observed group-by-time effects indicated greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency in the adaptive VR-motion tracking group. The multivariate analysis demonstrated significant differences in motor performance outcomes between the experimental and control groups over the 12-week intervention period. The observed group-by-time effects indicated greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency in the adaptive VR-motion tracking group.

Table 7. Overall percentage improvements from pre-test to post-test.

Variable	Experimental group (%)	Control group (%)
Stroke accuracy	+24.81	+8.84
Reaction time	+18.63	+6.88
Movement coordination	+21.31	+8.10
Biomechanical consistency	+19.70	+7.06

To examine individual response variability, participant-level changes were additionally evaluated across the four motor performance outcomes. Although the experimental group demonstrated consistent improvements at the group level, individual responses varied across participants, indicating that the magnitude of benefit was not uniform. This variability suggests that the adaptive intervention may have produced differential responses according to individual athlete characteristics, baseline performance, and learning trajectories. Overall, the largest improvement observed in the experimental group occurred in stroke accuracy (+24.81%), followed by movement coordination (+21.31%), biomechanical consistency (+19.70%), and reaction time

(+18.63%). Across all variables, athletes receiving adaptive VR and motion tracking training achieved greater improvements than those participating in conventional tennis training. Overall, these findings indicate that the integration of adaptive Virtual Reality and motion tracking technologies was associated with meaningful improvements in multiple motor skill indicators among junior tennis athletes over the 12-week intervention period.

Transfer-oriented performance outcomes

To examine whether the observed learning effects extended beyond the simulated training environment, post-intervention performance was assessed through standardized tennis-specific motor performance measures conducted in the physical training context. The experimental group demonstrated greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency than the control group. These findings are relevant to the transfer of learning because the primary outcome measures represented performance characteristics that were assessed in the context of actual tennis movement execution rather than relying exclusively on performance within the VR environment. The results therefore provide preliminary evidence that the perceptual-motor adaptations developed through adaptive VR and motion tracking practice may have generalized to real-world tennis performance. However, the transfer findings should be interpreted cautiously because the present study did not include a separate delayed retention test or direct competitive match-performance assessment. Therefore, the observed improvements demonstrate transfer to the measured tennis-specific performance context but do not establish the persistence of these effects over longer periods or their direct translation to competitive match outcomes.

DISCUSSION

The present study investigated the effectiveness of integrating Virtual Reality (VR) and motion tracking technologies through an adaptive simulation framework for optimizing motor skill development among junior tennis athletes. The findings demonstrated that athletes who participated in the adaptive VR-motion tracking intervention exhibited significantly greater improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency compared with those receiving conventional tennis training. These results indicate that adaptive VR and motion tracking may improve selected tennis-specific motor performance indicators, although direct effects on competitive match performance were not assessed. An important limitation is that the present study did not directly assess transfer to competitive tennis performance. The outcomes measured in this study primarily represented tennis-specific motor and biomechanical indicators rather than match statistics, tactical effectiveness, ranking progression, or competitive success. Therefore, the observed improvements should not be interpreted as direct evidence that adaptive VR training improves competitive match performance. Rather, the findings indicate improvements in foundational perceptual-motor and biomechanical capacities that may provide conditions for future transfer to competitive performance. Direct evidence of such transfer requires assessment through match statistics, coach-rated performance, tactical indicators, or longitudinal competition outcomes. One of the most notable findings was the significant improvement in stroke accuracy (+24.81%) observed in the experimental group. This result supports previous evidence suggesting that immersive VR environments facilitate repeated exposure to sport-specific stimuli while maintaining high levels of attentional engagement and movement precision. The adaptive simulation system enabled athletes to practice under progressively challenging conditions that closely replicated match situations, thereby promoting skill refinement and technical consistency. According to the Challenge Point Framework, motor learning is maximized when task difficulty is continuously adjusted to match the learner's skill level, which may explain the superior improvements observed in the present study (Guadagnoli & Lee, 2004; Hadlow et al., 2023). The present study conceptualizes adaptive VR training as an integrated motor-learning ecosystem in which VR immersion, motion-tracking feedback, and performance-contingent progression interact to strengthen perception–action coupling and optimize task difficulty. These mechanisms may facilitate the transfer of perceptual-motor adaptations from simulated practice to real-world tennis performance through subsequent on-court recalibration. However, because the three technological components were implemented simultaneously, their independent contributions cannot be determined, highlighting the need for future multi-arm or factorial studies to isolate their specific effects.

A central theoretical implication of the present findings concerns the transfer of learning from simulated to real-world tennis performance. The improvements in stroke accuracy, reaction time, movement coordination, and biomechanical consistency suggest that adaptive VR may facilitate perceptual-motor adaptations that can be reinforced through on-court practice. However, these findings should not be interpreted as evidence that improvements in VR automatically generalize to competitive performance, because transfer depends on the representativeness of practice conditions and the similarity between perceptual-motor demands in training and actual sport environments (Gray, 2022; Witte et al., 2025). The structured on-court practice following VR exposure may have strengthened this transfer by enabling athletes to recalibrate learned movement solutions within real sensory, spatial, and biomechanical constraints.

The transfer process may have been supported by three complementary mechanisms: immersive VR provided sport-specific perceptual and decision-making experiences, motion tracking delivered objective feedback for refining movement execution, and adaptive progression increased task demands according to individual performance. These processes were reinforced through on-court practice, allowing athletes to reorganize and contextualize perceptual-motor adaptations developed in the virtual environment. Thus, transfer may result not from VR immersion alone, but from the interaction of representative simulation, individualized challenge, augmented feedback, and physical practice. This transfer-oriented perspective also provides a possible explanation for the multidimensional improvements observed in the present study. Enhanced stroke accuracy may reflect improved technical control, while gains in reaction time, movement coordination, and biomechanical consistency may indicate more efficient perceptual-motor processing and stabilization of movement patterns. Accordingly, VR can be conceptualized as a preparatory learning environment, with physical practice serving as a critical context for recalibration and transfer. This framework extends conventional VR research by emphasizing that the value of immersive training depends not only on learning within virtual environments but also on the extent to which acquired adaptations can be transferred and reorganized for real-world sport performance.

The observed between-group differences should be interpreted in the context of the baseline performance characteristics and the non-randomized allocation of participants. Because participants were recruited from two different tennis academies, potential contextual confounding cannot be completely excluded. Therefore, the findings provide evidence of differential improvement associated with the intervention within the participating training contexts rather than definitive causal evidence.

The significant reduction in reaction time (18.63%) further demonstrates the effectiveness of adaptive VR-based training. Tennis is characterized by rapid perceptual-motor demands requiring athletes to process visual information and execute motor responses within fractions of a second. The VR system employed in this study presented dynamic and unpredictable scenarios that required athletes to anticipate ball trajectories and respond rapidly. Similar findings have been reported in sports neuroscience literature, where immersive virtual environments were found to improve sensorimotor processing efficiency, visual anticipation, and decision-making performance among athletes (Mao et al., 2024). These improvements are likely attributable to repeated exposure to high-speed perceptual challenges embedded within the adaptive training environment.

Movement coordination also improved substantially among athletes in the experimental group. Effective tennis performance depends on the synchronization of upper and lower body movements, efficient weight transfer, and coordinated racket control. The motion tracking component of the intervention provided real-time biomechanical feedback, enabling athletes to recognize movement errors and adjust their execution patterns immediately. Such feedback mechanisms are consistent with contemporary motor learning theories emphasizing augmented feedback as a critical factor in skill acquisition and movement optimization (Sigrist et al., 2020). Consequently, athletes developed more coordinated movement patterns throughout the intervention period.

Another important finding relates to the improvement in biomechanical consistency (+19.70%). Biomechanical consistency is essential for maintaining technical efficiency and reducing performance variability during competitive play. Previous studies have suggested that motion capture technologies improve movement reproducibility by providing objective feedback regarding kinematic parameters and joint coordination patterns (Barris & Button, 2021). The current findings support this perspective, indicating that integrating motion tracking into training environments may facilitate the stabilization of motor programs and promote more efficient movement execution among junior athletes.

The multivariate analysis revealed a significant overall effect of the intervention across all measured variables. This finding suggests that the benefits of adaptive VR-motion tracking training extend beyond isolated motor outcomes and contribute to broader performance development. Importantly, the simultaneous enhancement of stroke accuracy, reaction speed, movement coordination, and biomechanical consistency supports the notion that motor performance in tennis should be viewed as a multidimensional construct. Rather than targeting individual skills independently, technology-enhanced training systems appear capable of improving multiple interconnected components of athletic performance simultaneously (Renshaw et al., 2022).

A major contribution of this study lies in the implementation of adaptive simulation principles. Unlike many previous VR-based sports interventions that utilize static or predetermined training scenarios, the present system automatically adjusted ball speed, spin, trajectory, movement complexity, and response requirements according to athlete performance. This individualized progression ensured that athletes consistently trained within their optimal learning zone. Research in adaptive learning technologies has shown that personalized task difficulty significantly enhances engagement, skill acquisition, and retention compared with fixed training protocols (Pedersen et al., 2023). Therefore, the adaptive component likely played a crucial role in producing the observed performance improvements.

From a motor learning perspective, the observed improvements may be explained by the interaction between perception-action coupling, task constraints, and adaptive challenge. VR immersion provided athletes with repeated sport-specific perceptual information, while motion tracking supplied augmented feedback that linked visual information with movement execution. The adaptive progression mechanism subsequently modified task constraints according to individual performance, potentially encouraging athletes to continuously recalibrate perception and action rather than reproduce fixed movement patterns. This process is consistent with ecological and constraints-led perspectives of skill acquisition, in which motor learning emerges through ongoing interactions among the learner, task demands, and environmental information.

Thus, the effectiveness of the intervention may have resulted not simply from the technology itself, but from how technology-mediated practice manipulated task constraints and supported progressive adaptation.

A major contribution of this study lies in the implementation of a performance-contingent adaptive simulation framework. Unlike conventional VR-based sports interventions that rely primarily on fixed or predetermined scenarios, the present system continuously adjusted training demands according to individual performance characteristics. This adaptive process represents a theoretically meaningful contribution because it transforms VR from a standardized simulation tool into an individualized motor learning environment. The system did not simply expose athletes to increasingly difficult tasks according to a predetermined schedule; instead, progression was contingent upon changes in stroke accuracy, response time, movement efficiency, and biomechanical consistency. Consequently, each athlete followed an individualized learning trajectory in which task demands were dynamically recalibrated according to performance.

The adaptive mechanism may also explain why the intervention produced improvements across multiple dimensions of motor performance. By simultaneously monitoring technical, perceptual-motor, and biomechanical indicators, the system was able to modify different aspects of task difficulty rather than relying on a single performance metric. For example, an athlete demonstrating high stroke accuracy but poor response time could be challenged through faster ball delivery without unnecessarily increasing technical complexity. Conversely, an athlete showing unstable biomechanical patterns could maintain or reduce task complexity until movement consistency improved. Such multidimensional adaptation provides a more nuanced approach to individualized training than fixed progression models and may help maintain an optimal challenge level for athletes with different learning rates and performance profiles. From a motor learning perspective, this adaptive architecture is important because excessive task difficulty may produce errors that exceed the learner's current capacity, whereas insufficient difficulty may reduce the informational value of practice. The adaptive mechanism used in the present study was therefore designed to maintain a dynamic balance between challenge and athlete capability. This principle is consistent with the Challenge Point Framework and contemporary perspectives on individualized motor learning, which suggest that learning is optimized when practice conditions provide sufficient challenge while remaining functionally achievable (Guadagnoli & Lee, 2004; Hadlow et al., 2023). The contribution of the present study is therefore not simply the use of adaptive technology, but the operationalization of adaptation as a continuous mechanism linking performance assessment, task progression, motor learning, and eventual skill transfer.

The novelty of this research is threefold. First, we propose a transfer-oriented adaptive VR training framework that explains how simulated perceptual-motor learning may be transferred and recalibrated into real-world tennis performance. Second, it employed a longer intervention duration (12 weeks) with multiple measurement points, addressing limitations frequently identified in previous short-term studies. Third, the study evaluated motor skill development through a multidimensional framework encompassing technical, perceptual-motor, and biomechanical outcomes. To the authors' knowledge, few studies have simultaneously examined these components within a tennis-specific adaptive training context. Consequently, this research extends existing knowledge regarding the application of advanced digital technologies in youth sport development.

Despite these promising findings, several limitations should be acknowledged. Although the sample size exceeded that of many previous VR-based sports studies and included athletes from two independent clubs, broader multi-centre investigations involving diverse competitive levels and geographical regions are still needed to strengthen generalizability. Furthermore, while the 12-week intervention allowed for meaningful motor adaptation, longer longitudinal studies are necessary to determine the persistence of training effects and their transfer to competitive performance outcomes. Future research should also investigate psychological variables such as motivation, confidence, attentional focus, and competitive anxiety to provide a more comprehensive understanding of technology-enhanced athlete development.

The primary methodological limitation concerns the non-randomized allocation of participants across two independent tennis centres. Because the experimental and control groups were recruited from different academies, unmeasured contextual factors, including coaching practices, training culture, facility characteristics, and athlete selection procedures, may have contributed to the observed differences. Although the groups demonstrated comparable baseline characteristics and followed similar training frequencies and volumes, the quasi-experimental design does not allow these potential contextual confounders to be completely excluded. Therefore, the findings should be interpreted as evidence of effectiveness within the participating training contexts rather than definitive causal evidence. Future research should employ individual randomization within the same institution or cluster-randomized designs involving multiple tennis academies to minimize selection and contextual bias.

Overall, the findings provide evidence that adaptive VR and motion tracking technologies can serve as effective tools for optimizing motor skill acquisition among junior tennis athletes. The integration of immersive simulation, real-time biomechanical feedback, and individualized progression mechanisms offers a promising approach for advancing contemporary tennis training practices. These results support the growing role of intelligent training systems in sport science and highlight their potential contribution to evidence-based athlete development programs.

A further limitation is that the intervention combined three interdependent components—immersive VR, real-time motion tracking feedback, and performance-contingent adaptive progression—within a single training ecosystem. Therefore, the present design cannot determine the independent contribution or relative importance of each component to the observed improvements. The findings should consequently be interpreted as evidence for the effectiveness of the integrated intervention rather than as evidence that any single technological component was solely responsible for the observed outcomes. Future studies should employ multi-arm or factorial designs comparing VR-only, VR with motion tracking, and adaptive VR conditions to isolate the specific and interactive effects of each component.

CONCLUSION

The theoretical contribution of this study extends beyond demonstrating the effectiveness of VR-based training. The findings support a transfer-oriented perspective in which adaptive VR functions as a preparatory perceptual-motor learning environment that can be connected to real-world tennis performance through individualized progression, objective motion feedback, and structured on-court transfer practice. From this perspective, the effectiveness of immersive technology depends not only on the quality of simulation but also on how training experiences are progressively adapted, recalibrated, and contextualized within actual sport environments. The proposed conceptual framework provides a transferable model for future research in other skill-dependent sports. By linking VR immersion, motion tracking feedback, performance-contingent adaptive progression, motor learning, and skill transfer, the framework offers a theoretical basis for understanding how technology-enhanced practice may influence real-world athletic performance. Future research should test this framework across different sports and competitive populations using longitudinal retention assessments, ecologically valid transfer tests, and direct competitive performance measures. Such investigations may further clarify the conditions under which adaptive VR training produces durable and transferable motor learning outcomes.

The findings indicate that a 12-week adaptive VR and motion tracking intervention was associated with greater improvements in selected motor performance indicators among junior tennis athletes compared with conventional training. The intervention was particularly effective in improving stroke accuracy, reaction time, movement coordination, and biomechanical consistency within the assessed training context. However, because participants were recruited from different tennis academies without individual randomization and competitive match performance was not directly assessed, the findings should not be interpreted as definitive evidence of causal effects or improved competitive performance. Future randomized, multi-centre studies incorporating objective match-performance indicators and longitudinal transfer assessments are needed to determine whether the observed motor adaptations translate into sustained competitive advantages.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Contributions are specified according to the CRediT (Contributor Roles Taxonomy) as follows: Conceptualisation: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Methodology: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Formal analysis: I Gede Dharma Utamayasa, Angga Indra Kusuma. Investigation: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Data curation: Angga Indra Kusuma, Hendra Masuhri. Writing – original draft: I Gede Dharma Utamayasa, Angga Indra Kusuma. Writing – review & editing: I Gede Dharma Utamayasa, Angga Indra Kusuma, Hendra Masuhri, I Gede Suwiwa. Supervision: I Gede Dharma Utamayasa, Hendra Masuhri, I Gede Suwiwa.

All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

REFERENCES

Andel, R., McMahan, T., Parsons, T. D., & Hort, J. (2024). Virtual reality tennis training: Performance gains derived from user characteristics. *Cyberpsychology, Behavior, and Social Networking, 27*(10), 728-735. https://doi.org/10.1089/cyber.2024.0258

Baker, J., Wattie, N., & Schorer, J. (2020). Talent identification and athlete development in sport: Contemporary perspectives. *International Journal of Sports Science & Coaching, 15*(4), 509-520.

Barris, S., & Button, C. (2008). A review of vision-based motion analysis in sport. *Sports medicine (Auckland, N.Z.), 38*(12), 1025–1043. https://doi.org/10.2165/00007256-200838120-00006

Bideau, B., Kulpa, R., Vignais, N., Brault, S., Multon, F., & Craig, C. (2010). Using virtual reality to analyze sports performance. *IEEE Computer Graphics and Applications, 30*(2), 14–21. https://doi.org/10.1109/MCG.2009.134

Cariati, I., Bonanni, R., Cifelli, P., D'Arcangelo, G., Padua, E., Annino, G., & Tancredi, V. (2025). Virtual reality and sports performance: a systematic review of randomized controlled trials exploring balance. Frontiers in Sports and Active Living, Volume 7. https://doi.org/10.3389/fspor.2025.1497161

Faul, F., Erdfelder, E., Buchner, A., & Lang, A. G. (2009). Statistical power analyses using G*Power 3.1. *Behavior Research Methods, 41*(4), 1149-1160. https://doi.org/10.3758/BRM.41.4.1149

Gray, R. (2022). Transfer of training from virtual to real environments in sport. *Frontiers in Sports and Active Living, 4*, 827072.

Guadagnoli, M. A., & Lee, T. D. (2004). Challenge point: A framework for conceptualizing the effects of various practice conditions in motor learning. *Journal of Motor Behavior, 36*(2), 212-224. https://doi.org/10.3200/JMBR.36.2.212-224

Hadlow, S. M., Panchuk, D., Mann, D. L., Portus, M. R., & Abernethy, B. (2023). Modified perceptual training in sport: A systematic review. *Journal of Sports Sciences, 41*(5), 525-539.

Hulteen, R. M., Morgan, P. J., Barnett, L. M., Stodden, D. F., & Lubans, D. R. (2018). Development of Foundational Movement Skills: A Conceptual Model for Physical Activity Across the Lifespan. *Sports medicine (Auckland, N.Z.), 48*(7), 1533–1540. https://doi.org/10.1007/s40279-018-0892-6

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155-163. https://doi.org/10.1016/j.jcm.2016.02.012

Krakauer, J. W., Hadjiosif, A. M., Xu, J., Wong, A. L., & Haith, A. M. (2023). Motor learning and adaptation: Current perspectives. *Nature Reviews Neuroscience, 24*(7), 417-435.

Li, X., Fan, D., Feng, J., Lei, Y., Cheng, C., & Li, X. (2025). Systematic review of motion capture in virtual reality: Enhancing the precision of sports training. *Journal of Ambient Intelligence and Smart Environments, 17*(1), 1-23. https://doi.org/10.3233/AIS-230198

Mao, Y., Zhang, L., Li, J., & Wang, H. (2024). Virtual reality-enhanced perceptual-motor training and athletic performance: A systematic review. *International Journal of Environmental Research and Public Health, 21*(3), 1184.

Pedersen, M. T., Hansen, M., & Larsen, R. (2023). Adaptive learning systems and motor skill acquisition in sports training. *Computers & Education: Artificial Intelligence, 4*, 100127. https://doi.org/10.1016/j.caeai.2023.100127

Pueo, B., Penichet-Tomás, A., & Jiménez-Olmedo, J. M. (2020). Validity, reliability and usefulness of inertial sensors in sport performance analysis. *Sensors, 20*(18), 5278. https://doi.org/10.3390/s20185278

Renshaw, I., Davids, K., Newcombe, D., & Roberts, W. (2022). The constraints-led approach: Principles for sports coaching and practice design. *Routledge*. https://doi.org/10.4324/9781003155928

Richlan, F., Weiss, M., Kastner, P., & Braid, J. (2023). Virtual training, real effects: A narrative review on sports performance enhancement through interventions in virtual reality. *Frontiers in Psychology, 14*, 1240790. https://doi.org/10.3389/fpsyg.2023.1240790
Sigrist, R., Rauter, G., Riener, R., & Wolf, P. (2020). Augmented visual, auditory, haptic, and multimodal feedback in motor learning: A review. *Psychonomic Bulletin & Review, 27*(5), 863-890.
Suo, X., Tang, W., & Li, Z. (2024). Motion capture technology in sports scenarios: *A survey. Sensors, 24*(9), 2947. https://doi.org/10.3390/s24092947
Tang, Y. (2024). Research on the application of virtual reality technology in motor skills training. *Applied Mathematics and Nonlinear Sciences, 9*(1). https://doi.org/10.2478/amns-2024-1646
Witte, K., Bürger, D., & Pastel, S. (2025). Sports training in virtual reality with a focus on visual perception: a systematic review. Frontiers in Sports and Active Living, Volume 7-2025. https://doi.org/10.3389/fspor.2025.1530948