

Seasonal changes in physical fitness and body composition and their associations with external match load in elite youth football players

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ABSTRACT

Purpose: To compare seasonal changes in body composition and physical fitness and examine their associations with external match load in elite youth football players. **Methods:** Twenty-nine players from the U18 ($n = 14$) and U21 ($n = 15$) squads were assessed during two competitive periods (First and Second Phase). Body composition included muscle mass (%MM), fat mass (%FM), and the sum of 6 skinfolds (6skf). Physical fitness assessments comprised countermovement jump (CMJ), 10-m (T10) and 30-m sprint time (T30), change-of-direction ability (COD), kicking velocity (KV), and maximal oxygen uptake (VO_{2max}). External match load was quantified using GPS technology. **Results:** Both categories showed significant improvements in body composition, with higher %MM and lower %FM and 6skf ($p < .05$). CMJ, T30, and KV also improved significantly, whereas VO_{2max} remained unchanged. Correlation analyses identified significant associations between physical fitness, body composition, and external match load, with more relationships observed in U18 than U21 players. **Conclusions:** Elite youth football players improved primarily in neuromuscular performance and body composition across the season. The greater number of associations observed in U18 players represents an exploratory pattern and should not be interpreted as evidence of stronger relationships between physical qualities and match performance compared with U21 players.

Keywords: performance analysis; athletic performance; monitoring; physiologic; muscle strength; anthropometry; physical endurance.

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INTRODUCTION

Performance in football is a multifactorial phenomenon resulting from the interaction of physical, technical, tactical, and physiological variables during competition (Villaseca-Vicuña, Barrera-Díaz, et al., 2026). Among these determinants, physical fitness and body composition play a fundamental role in meeting the intermittent high-intensity demands inherent to the game (Villaseca-Vicuña, Molina-Sotomayor, et al., 2021). Modern football requires players to perform repeated accelerations, decelerations, sprints, and changes of direction while simultaneously maintaining high levels of aerobic capacity and neuromuscular performance (Bangsbo et al., 2006). Consequently, the assessment of neuromuscular variables such as countermovement jump performance, linear sprint speed, change of direction ability, kicking velocity, and maximal oxygen uptake has become common practice in high-performance environments (Pérez-Contreras et al., 2022; Villaseca-Vicuña, Medrano, et al., 2025). In addition, body composition indicators such as percentage of muscle and adipose mass have also been associated with physical fitness and match demands, as higher levels of body fat may negatively affect sprinting speed, acceleration capacity, and overall competitive performance (Rios-Limas et al., 2025).

Throughout a competitive season, football players are exposed to fluctuations in training and match loads that may induce adaptations in physical fitness and neuromuscular performance (Clemente et al., 2019; Malone et al., 2015). Several studies have reported improvements in variables such as neuromuscular and sprint performance during the competitive period, particularly in young players who are still undergoing physical development (Buchheit & Mendez-Villanueva, 2013). Simultaneously, advances in monitoring technologies have enabled the accurate quantification of external load during competition through variables such as total distance covered, high-speed running distance, sprint distance, the number of accelerations and decelerations, and inertial sensor-derived metrics such as player load (Cummins et al., 2013). Within this context, some investigations suggest that players with higher levels of physical fitness tend to tolerate greater competitive demands or exhibit higher external load values during matches, highlighting the close relationship between physical capacities and match performance outcomes (Rios-Limas et al., 2025; Villaseca-Vicuña, Otero-Saborido, et al., 2021).

Despite the growing number of studies examining match demands and physical profiles in football, there remains limited evidence simultaneously investigating seasonal changes in physical fitness, body composition, and their relationship with external match load in elite youth players. Understanding these interactions is particularly relevant in players approaching senior professional football, as they are exposed to demanding competitive schedules while continuing to experience biological development and physical maturation processes (Villaseca-Vicuña, Otero-Saborido, et al., 2021). Furthermore, identifying which physical qualities are associated with greater competitive demands may provide valuable information for optimising training programmes, improving performance monitoring strategies, and supporting players' long-term development (Ford et al., 2020). However, evidence describing these relationships across different competitive periods within the same season remains scarce, particularly in South American youth football settings. Moreover, much of the available evidence on longitudinal physical development and match-load demands in academy football has been derived from European cohorts. Evidence from South American professional academies remains comparatively limited, despite differences in competitive structures, developmental pathways, and training environments that may influence the expression of physical performance (Villaseca-Vicuña, Cursach, et al., 2025; Villaseca-Vicuña, Merino-Muñoz, et al., 2026). Therefore, examining players from a South American professional academy provides an opportunity to extend the geographical scope of the existing literature while identifying context-specific patterns that warrant validation across different academy environments.

Therefore, the present study had two aims: (i) to compare changes in body composition and physical fitness between two competitive periods (First Phase vs. Second Phase) in elite youth football players; and (ii) to analyse the associations between physical fitness, body composition, and external load variables during official competition through a category-stratified analysis (U18 and U21), to explore potential age-category-specific patterns in the coupling between physical profiles and external match-load expression. Based on previous literature, it was hypothesised that: (i) neuromuscular performance and sprint capacity would improve throughout the competitive season; and (ii) players with higher levels of physical fitness and lower levels of adiposity would exhibit greater external load values during official competition, with these associations potentially differing according to competitive category.

MATERIAL AND METHODS

Design

The present study adopted a longitudinal observational design with repeated measures collected across two competitive periods within the same season (First Phase and Second Phase). Body composition and physical fitness were assessed at two time points: prior to the start of the First Competitive Phase and prior to the start of the Second Competitive Phase. In addition, external match load variables were recorded during official matches throughout each competitive period.

This design enabled the analysis of within-subject changes in body composition and physical fitness across the season, as well as the examination of the relationships between players' physical profiles and the external load demands experienced during competition. To account for differences associated with biological development and competitive context, all analyses were conducted separately for the U18 and U21 categories.

Training programme and weekly microcycle. Throughout the observation period, both age categories followed a structured match-day-based weekly microcycle. The typical microcycle included post-match recovery or compensatory work (MD+2), lower-body strength training (MD-4), duration-oriented conditioning (MD-3), speed-oriented training (MD-2), pre-match activation (MD-1), official competition (MD), and passive recovery (MD+1). Physical preparation was integrated with technical and tactical contents according to the proximity to match day. Conditioning included continuous aerobic work, intermittent running prescribed relative to YYIRT-L1 performance, small-sided games, strength training, sprinting, and change-of-direction exercises. The general structure and main training contents were maintained across the First and Second Phases and are detailed in Supplementary Table S1. Each observation phase comprised 10 official matches, resulting in a comparable number of competitive fixtures between phases. Official competition was generally scheduled once per weekly microcycle (MD), although individual match exposure varied according to player selection and playing time. Individual session-level internal and external training loads were not included in the present analysis; therefore, the programme description provides contextual information regarding training exposure rather than a quantitative assessment of the specific training dose received by each player.

Participants

A non-probabilistic convenience sampling approach was employed, involving youth football players from the academy system of a professional first-division football club in Chile. The competitive categories were defined by the national football federation according to players' year of birth. For the purposes of the present study, players from the U18 ($n = 14$) and U21 ($n = 15$) categories were included. The U18 players had a mean body mass of 71.90 ± 7.74 kg and a mean height of 178.43 ± 5.81 cm, while the U21 players presented a mean body mass of 72.22 ± 8.01 kg and a mean height of 175.79 ± 7.47 cm.

Table S1. Schematic representation of the microcycle structure according to the training tasks and contents implemented.

MD + 2	MD - 4	MD - 3	MD - 2	MD - 1	MD	MD + 1
Active recovery/ compensation	Strength	Duration	Velocity	Activation	Match day	Off
Physical training Core training (10') dynamic and isometric contraction exercises Upper-body strength 3–5 sets/3–6 r 30–60% 1RM Bench Press Pull-Ups TRX Pull-Ups Shoulder Push- Ups Recovery Work (>60 min players): —Aerobic continuous run or bike: 15–20' at 60–65% HRmax —Stretching and mobility (10–15'): assisted and with foam roller Complementary Work (<60 min players): —Small-sided games (3 × 4', 2' rec, 6v6–8v8) —Intermittent runs: 1–2 sets × 6–8 reps of 100 m (90–120% YYIRT-L1)	Physical training Core training (10') dynamic and isometric contraction exercises dynamic and isometric contraction exercises Lower- body strength 3–5 sets/3–6 r 30–60% 1RM Squat Deadlift Hip thrust TEC/TAC (~60') Duelling actions, few players in small spaces <60 m ² pp	Physical training Core training (10') dynamic and isometric contraction exercises Upper-body strength 3–5 sets/3– 6 r 30–60% 1RM Bench Press Pull- Ups TRX Pull- Ups Shoulder Push-Ups Intermittent training 1–2 sets × 6–8 reps of 100 m at 90–120% YYIRT-L1 TEC/TAC (~90') A greater number of players in larger playing spaces >90 m ² pp	Physical training Core training (10') dynamic and isometric contraction exercises Speed Block (20'): Unresisted sprints Linear sprints from 10 m to 30 m Change of direction and agility training from 10 m to 20 m TEC/TAC (~80') Fewer players in larger playing spaces >90 m ² pp Defensive set plays	Physical training Coordination drills (15') Individual and collective techniques with the ball TEC/TAC (~50') Few players in small spaces <60 m ² pp Offensive set plays	Football warm up (25') General exercises for joint mobility, control, and passing, games in reduced spaces, defensive block work, and offensive block work Competition	Passive recovery
Cool-down (10')	Cool-down (10')	Cool-down (10')	Cool-down (10')	Cool-down (10')	Cool-down (10')	

Procedures

Physical fitness and body composition were assessed at two time points during the competitive season: immediately prior to the First Competitive Phase and immediately prior to the Second Competitive Phase. Subsequently, 10 official matches were monitored during each competitive period. For each player, external match-load variables were averaged across the 10 monitored matches within each competitive phase, generating one representative value per external match-load variable for each phase. For the association analyses, each physical fitness and body composition assessment was paired exclusively with the average external match-load data obtained during the corresponding competitive phase. Thus, First Phase assessments were associated with First Phase match-load data, whereas Second Phase assessments were associated with Second Phase match-load data. Fitness assessments and match-load data from temporally different phases were not paired. Data were structured at the player-phase level. Each of the 14 U18 players and 15 U21 players contributed one record from the First Phase and one record from the Second Phase, resulting in 28 and 30 player-phase observations, respectively. Each record paired the physical fitness and body-composition assessment performed for that competitive phase with the corresponding average external match-load data from the 10 monitored matches. Therefore, individual player-match observations were not entered as separate cases in the correlation analyses. All assessments were conducted in the morning under controlled environmental conditions (approximately 15°C and 75% relative humidity). To minimise the effects of fatigue, participants were instructed to refrain from strenuous physical activity for at least 24 hours prior to testing (Villaseca-Vicuña, Medrano, et al., 2025). Before the assessments, each category completed a standardised warm-up protocol supervised by its strength and conditioning coach, consisting of a general phase (light running, multidirectional movements, and dynamic stretching), followed by a specific phase including exercises related to the requirements of each test.

All players were familiar with the testing procedures, as these assessments form part of the club's annual physical fitness and body composition testing battery within its youth development programme (Figure 1). Participants were instructed to perform each test with maximal effort. All physical assessments were conducted on an artificial turf surface, with players wearing football boots appropriate for this type of playing surface.

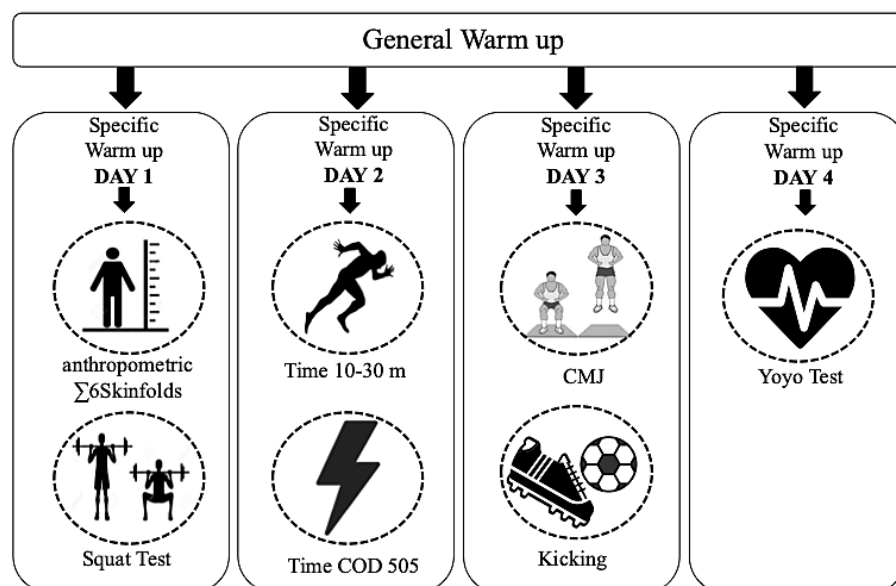


Figure 1. Body composition and physical fitness assessments.

Body composition

The weight and height of each player were measured using a scale with a height gauge (Seca 700®, Hamburg, Germany). In addition, the sum of 6 skinfolds (6skf: tricipital, subscapular, supraspinal, abdominal, medial thigh and calf maximum) was recorded, using these data to estimate the percentage of fat mass (%FM) and the percentage of muscle mass (%MM). All procedures were performed in accordance with the standards of the International Society for the Advancement of Kineanthropometry (ISAK) and were performed by a certified ISAK III specialist, belonging to the football club's staff. Skinfold measurements were performed with a high-precision (0.2 mm) thin-guide caliper (Rosscraft®, British Columbia, Canada).

Squat test

This test has been validated to assess lower limb muscle strength levels in footballers (Pareja-Blanco et al., 2017). Before the measurement, each player performed a specific warm-up of 3 sets and 3 repetitions with a load of 20 kg. In the evaluation, each player performed 1 set of 3 repetitions, with each load of: 20, 30, 40, 50, 60, 70 and 80 kg respectively, with a recovery of 3 minutes between sets. The concentric phase of the exercise was required to be executed at the maximum possible speed. The incremental test was completed after the final absolute load of 80 kg, and no repetitions were performed to muscular failure. Two variables were recorded: a) relative strength (RS), obtained from the ratio between estimated 1RM and body weight; and b) estimated one-repetition maximum (1RM), determined from the mean propulsive velocity (MPV) recorded during the final absolute load of 80 kg using the equation proposed by Pareja-Blanco et al. (2020). No within-set velocity-loss criterion was applied, as the purpose of the incremental test was to estimate 1RM from the MPV recorded at the final absolute load rather than to determine muscular failure or terminate the test according to a predefined velocity-loss threshold. The aforementioned variables were determined using the linear encoder (ADR encoder®, Toledo, Spain). Equation to calculate the 1RM in the squat from the MPV at the last load:

$$\%1RM = (-42.196 \times MPV^2) - (31.018 \times MPV) + 112.937$$

Linear sprint time in 10 (T10) and 30 meters (T30)

This test is commonly used to assess maximum running speed in footballers (Villaseca-Vicuña et al., 2024). Prior to the evaluation, the players performed a specific warm-up, which included five progressive 30-meter runs. Each player performed three 30-m attempts, with three minutes of recovery between attempts. The starting position was standing, with the forward foot placed just behind a line located 0.5 meters from the first photoelectric cell (Witty gate, Microgate®, Bolzano, Italy), to avoid premature interruptions of the light beam with the head or arms. Photoelectric cells were placed at the starting line, 10 meters, and 30 meters, recording the time from 0 to 10 meters (T10) and from 0 to 30 meters (T30). For the analysis, the best time of the three attempts was considered.

Change of direction 505 modified (COD)

Prior to the test, a standardised warm-up was carried out by the physical trainer, which consisted of 6 accelerations and a 5-m deceleration. The protocols for this test have already been documented in the literature (Pérez-Contreras et al., 2024). Using a single-beam photocell (Witty gate, Microgate®, Bolzano, Italy), positioned at the start/finish gate at a vertical height of 1 meter, players began with one foot 0.5 meters behind the gate, sprinted forward, stepped on the 5-m mark (white tape), and returned through the gate. A mark was placed beyond the gate to encourage players to continue running through the finish, and a researcher verbally encouraged them not to stop until they crossed the mark. Four attempts were performed, with two changes of direction completed for each side; the result was obtained by averaging the two valid attempts for each side. When a player did not reach the indicated 5-m mark, the attempt was considered null and repeated until two valid attempts were obtained. Players had 2 minutes of rest between attempts.

Countermovement jump (CMJ)

This test is usually done to measure the power of the lower limbs of football players (Kobal et al., 2016; Romero-Caballero et al., 2021). Before performing the test, each player performed a specific 5-jump warm-up to a jump box, the target surface of which was 40 cm from the ground. In the test, participants made 3 attempts. The starting position is upright with the hands on the waist throughout the test to eliminate any influence of arm swing. From this position the participant quickly bends the knees to approximately 90° and then immediately pushes off to jump vertically as high as possible, landing on both feet at the same time and with the knees extended (Kobal et al., 2016; Romero-Caballero et al., 2021). If the evaluator observed an execution error, the jump was invalidated and the execution was repeated. This test was evaluated using an infrared platform (Optojump Microgate® contact platform, Bolzano, Italy), with 3 minutes of rest between repetitions. The jump height (cm) was recorded and the best result was selected.

Kicking velocity (KV)

This physical-technical test assesses kicking velocity, a parameter widely analysed in footballers (Rada et al., 2019). Before the measurement, each player performed a specific warm-up, which consisted of 10 long passes with the instep. During the evaluation, the players executed three attempts with the dominant leg, using the full instep and with three minutes of recovery between each attempt. For the statistical analysis, the highest recorded velocity was considered. The players were instructed to kick the ball with the maximum possible speed, directing it towards a target of 1 meter in diameter, located in the centre of the goal (Rada et al., 2019). The ball remained static 8 meters from the goal (Molten Vantaggio 5000® ANFP 2023 Professional Ball, Hiroshima, Japan), allowing an approach run of 1 meter. A speed measuring radar (Supido Multideporte®, Blackpool, United Kingdom) was used. The radar was positioned 1 m behind the goal, according to the specific instructions of the radar (Díez-Fernández et al., 2022). If the execution did not meet the established criteria (e.g., contact with an inappropriate area of the foot or lack of precision in the direction of the shot), the attempt was discarded and repeated.

Maximal oxygen uptake (VO_{2max})

VO_{2max} was estimated using the Yo-Yo Intermittent Recovery Test Level 1, a field-based test widely used to assess intermittent endurance capacity in football players (Pérez-Contreras et al., 2022). Prior to testing, all players completed a standardised warm-up consisting of 10 submaximal 20-m shuttle runs with changes of direction. Participants performed one maximal attempt following the protocol described by Bangsbo et al. (2006). The total distance covered (m) during the Yo-Yo IR1 was recorded and subsequently used to estimate maximal oxygen uptake (VO_{2max} ; $ml \cdot kg^{-1} \cdot min^{-1}$) using the following equation:

$$VO_{2max} = [Yo-Yo IR1 \text{ distance (m)} \times 0.0084] + 36.4.$$

The estimated VO_{2max} value was used as the aerobic performance indicator in the statistical analyses (Bangsbo et al., 2006).

External load: GPS monitoring

Players' external load during each training session and match was monitored using GPS devices (WIMU Pro®, RealTrack Systems, Almería, Spain), with a sampling frequency of 10 Hz and an integrated 3D accelerometer operating at 100 Hz. Each device was secured in a neoprene vest worn tightly between the scapulae to ensure accurate data collection. The variables considered for analysis included total distance (TD), high-speed running (HSR; $>19.8 \text{ km/h}$), peak speed (PS), number of accelerations (ACC) and decelerations (DEC) greater than 3 m/s^2 , and player load (PL). These metrics are commonly used to monitor

training load and to assess and report player performance during official football matches in men's football (Stevens et al., 2017).

Statistical analysis

Data are presented as mean $\pm$ standard deviation ($M \pm SD$). Normality was assessed using the Shapiro–Wilk test, and homogeneity of variance was examined using Levene's test when appropriate. Changes between the First and Second Competitive Phases were assessed using paired-samples t-tests for normally distributed variables and Wilcoxon signed-rank tests when normality assumptions were not met.

The magnitude of within-player differences between competitive phases was quantified using Cohen's d for paired samples, calculated as the mean of the paired differences divided by the standard deviation of the paired difference scores. Effect-size signs were expressed in the direction of change from the First Phase to the Second Phase (Second Phase – First Phase), consistent with the percentage-change calculation. Ninety-five percent confidence intervals (95% CI) for Cohen's d were reported to indicate the precision of the effect-size estimates. Effect sizes were interpreted according to their absolute magnitude as trivial (<0.20), small ($0.20–0.59$), moderate ($0.60–1.19$), large ($1.20–1.99$), and very large (≥ 2.00). To complement the group-level pre–post comparisons, individual within-player changes were also visualized for each physical fitness and body-composition variable. Individual paired trajectories were displayed by connecting each player's First Phase and Second Phase values, thereby illustrating the direction and inter-individual variability of seasonal changes. Percentage change ($\Delta\%$) was calculated as $[(\text{Second Phase} - \text{First Phase}) / \text{First Phase}] \times 100$. These individual trajectories were used descriptively and were not intended to classify players as responders or non-responders.

For the association analyses, data were structured at the player-phase level. Each of the 14 U18 players and 15 U21 players contributed one phase-specific record from the First Phase and one from the Second Phase, resulting in 28 and 30 player-phase observations, respectively (14×2 for U18 and 15×2 for U21). Thus, the analytical unit represented a player within a specific competitive phase rather than an individual match observation. Pearson's correlation coefficients were used to examine relationships between body composition, physical fitness, and external match-load variables when normality assumptions were met, whereas Spearman's rho was applied when these assumptions were not satisfied. Correlation magnitudes were interpreted as trivial ($<.10$), small ($.10 - .29$), moderate ($.30 - .49$), large ($.50 - .69$), very large ($.70 - .89$), and nearly perfect ($\geq .90$).

Given the exploratory nature of the association analyses, correlation coefficients were primarily used to describe the magnitude and direction of potential relationships between physical and anthropometric characteristics and external match-load variables within each category. Accordingly, these analyses were considered hypothesis-generating rather than confirmatory. Statistically significant associations identified in the correlation analyses were subsequently explored using simple linear regression models to further characterise the strength and direction of these relationships. Statistical significance was set at $p \leq .05$. All statistical analyses were conducted separately for U18 and U21 players using JASP version 0.19.1 (JASP Team, University of Amsterdam, The Netherlands). Graphical representations of the simple linear regression analyses were generated using GraphPad Prism version 10.3.1 (GraphPad Software, LLC, Boston, MA, USA).

Ethical considerations

All participants were informed about the assessment and monitoring procedures conducted throughout the competitive season and provided informed consent. For players under 18 years of age, parents or legal

guardians were informed, prior to the beginning of the season and through the club's institutional meetings, about the routine physical assessment and performance-monitoring procedures implemented throughout the season, and provided informed consent for the players' participation in these procedures. The players were also informed about the assessments and their use as part of the club's performance-monitoring system. All measurements analysed in this study were part of the club's routine physical, anthropometric, and match-load monitoring procedures and were not introduced specifically for research purposes. Therefore, the study involved no experimental interventions, modifications to regular training practices, or additional procedures or risks beyond those inherent to routine football training, testing, and competition. All players held valid federation licences and had completed the medical evaluations required by the Chilean Football Federation before the beginning of the season. All procedures were conducted in accordance with the ethical principles of the Declaration of Helsinki (World Medical Association, 2013). The study was conducted using data obtained as part of the club's routine performance assessment and monitoring practices, following the ethical considerations applicable to sports science research and monitoring (Winter & Maughan, 2009).

RESULTS

Table 1 presents the changes in body composition and physical fitness variables between the First Phase and Second Phase in U21 players. Significant improvements were observed in %MM, CMJ, KV, and T30, together with significant reductions in %FM and 6skf (all $p < .001$), with moderate-to-large effect sizes. Conversely, T10 increased significantly, indicating a decline in short-distance acceleration performance. No significant changes were found in VO_{2max} , COD Right and Left and 1RM.

Table 1. Changes in body composition and physical fitness in U21 players.

Variable	First phase (M ± SD)	Second phase (M ± SD)	%	p value	Cohen's d [95% CI]	Magnitude
MM (%)	50.1 ± 1.94	51.1 ± 2.39	1.89	<.001	1.685 [0.875, 2.472]	Large
FM (%)	20.9 ± 2.53	19.3 ± 2.66	-7.74	<.001	-1.543 [-2.290, -0.772]	Large
6skf (mm)	43.0 ± 13.2	38.5 ± 13.1	-10.2	<.001	-1.227 [-1.892, -0.538]	Large
CMJ (cm)	39.7 ± 3.86	44.2 ± 5.30	11.48	<.001	1.367 [0.643, 2.068]	Large
VO_{2max} (ml·kg ⁻¹ ·min ⁻¹)	60.7 ± 3.77	60.6 ± 3.80	-0.26	.789	-0.071 [-0.576, 0.437]	Trivial
T30 (s)	4.09 ± 0.14	3.96 ± 0.14	-3.04	<.001	-1.826 [-2.653, -0.975]	Large
T10 (s)	1.60 ± 0.10	1.67 ± 0.09	3.81	.005	0.860 [0.253, 1.446]	Moderate
COD right (s)	2.40 ± 0.09	2.45 ± 0.08	1.83	.097	0.460 [-0.081, 0.986]	Small
COD left (s)	2.39 ± 0.08	2.44 ± 0.08	2.09	.212	0.337 [-0.189, 0.853]	Small
1RM (kg)	155 ± 17.1	158 ± 26.3	1.67	.618	0.132 [-0.379, 0.638]	Trivial
Kicking (km/h)	103 ± 4.59	108 ± 3.42	4.76	<.001	1.473 [0.721, 2.202]	Large

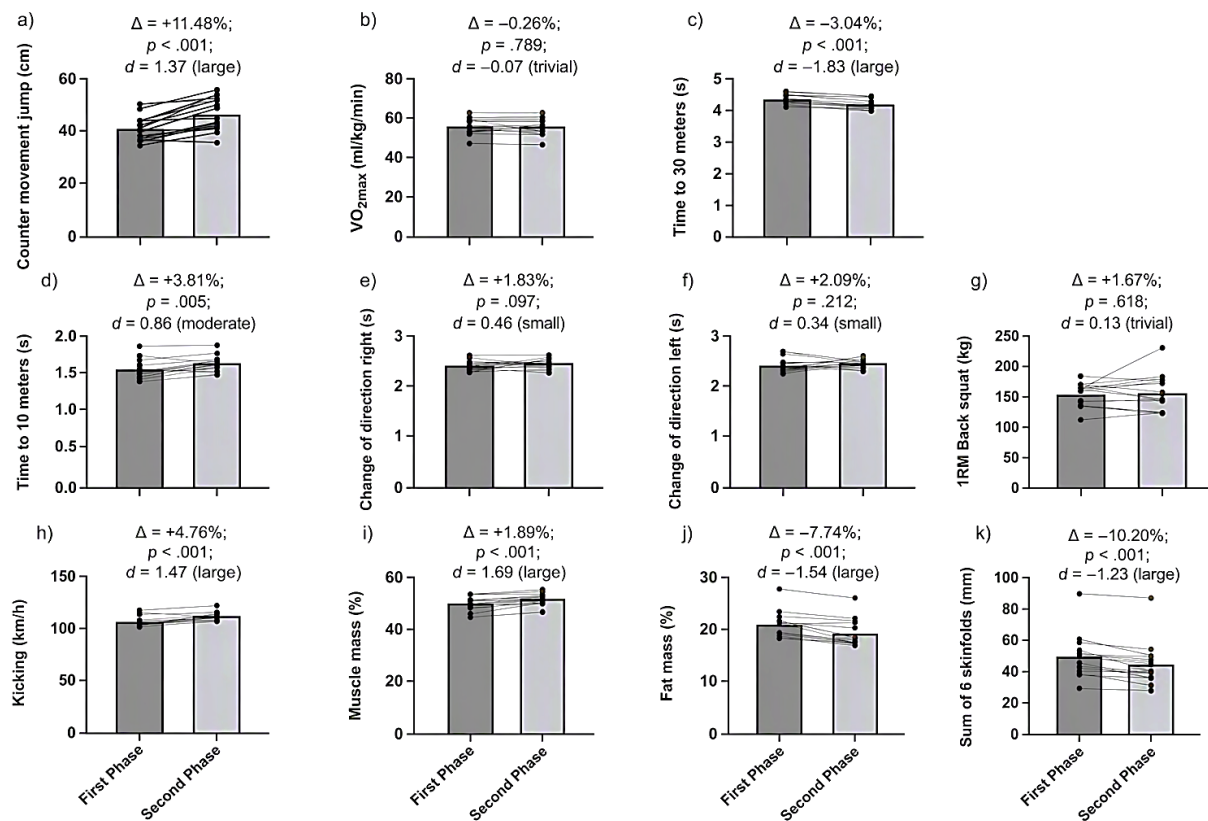
Note. M = mean; SD = standard deviation; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; CI = confidence interval. Cohen's d = standardised effect size for paired samples. Effect-size magnitude was interpreted using the absolute value of Cohen's d: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥2.00).

Table 2 presents the changes in body composition and physical fitness variables between the First Phase and Second Phase in U18 players. Significant improvements were observed in %MM, CMJ, KV, and T30, together with significant reductions in %FM and 6skf (all $p < .05$), with moderate-to-large effect sizes. However, T10 and COD Right increased significantly, indicating a decline in acceleration and change-of-direction performance, respectively. No significant changes were observed in VO_{2max} , COD Left, and 1RM.

Table 2. Changes in body composition and physical fitness in U18 players.

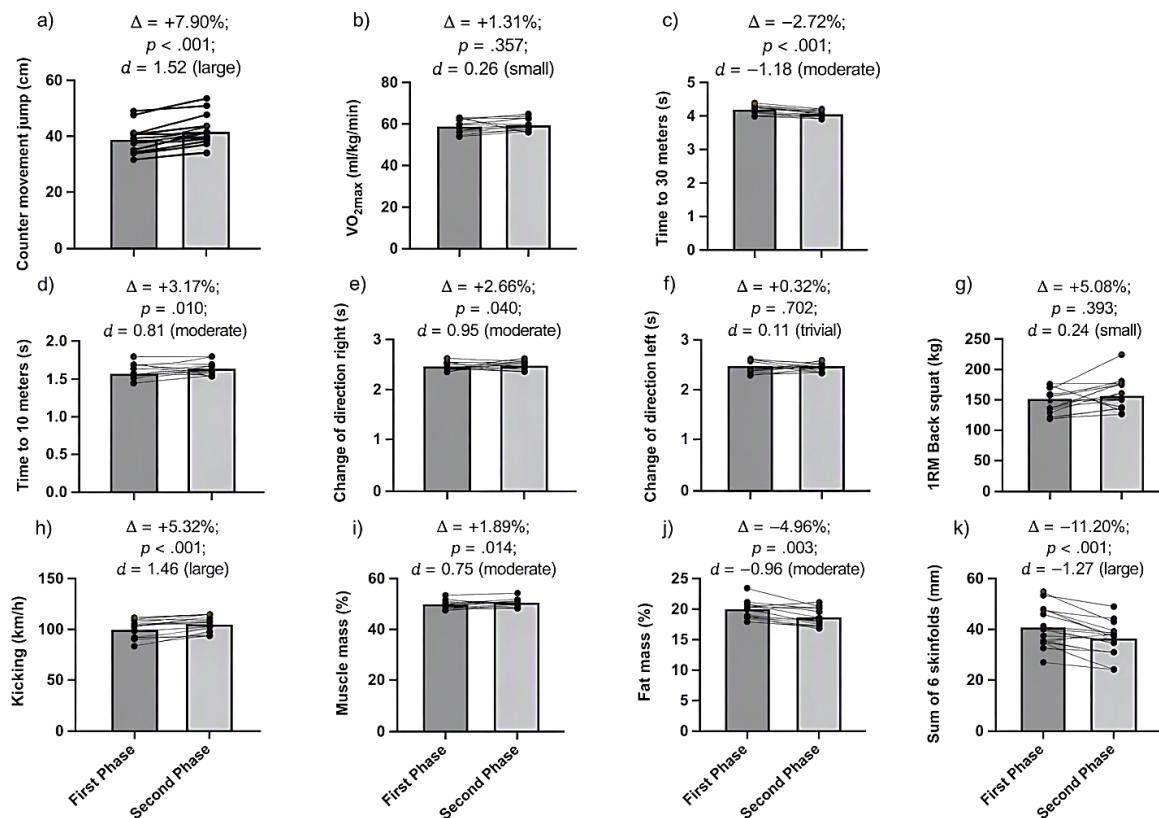
Variable	First phase (M ± SD)	Second phase (M ± SD)	%	p value	Cohen's d [95% CI]	Magnitude
MM (%)	50.41 ± 1.74	51.3 ± 1.61	1.89	.014	0.754 [0.146, 1.341]	Moderate
FM (%)	20.1 ± 1.39	19.1 ± 1.54	-4.96	.003	-0.959 [-1.585, -0.308]	Moderate
6skf (mm)	40.6 ± 7.42	36.0 ± 6.55	-11.2	<.001	-1.272 [-1.972, -0.546]	Large
CMJ (cm)	38.8 ± 4.41	41.9 ± 4.69	7.90	<.001	1.519 [0.726, 2.285]	Large
VO _{2max} (ml·kg ⁻¹ ·min ⁻¹)	60.2 ± 3.14	61.2 ± 2.65	1.31	.357	0.255 [-0.282, 0.783]	Small
T30 (s)	4.18 ± 0.13	4.06 ± 0.09	-2.72	<.001	-1.183 [-1.861, -0.480]	Moderate
T10 (s)	1.61 ± 0.04	1.66 ± 0.09	3.17	.010	0.810 [0.191, 1.407]	Moderate
COD right (s)	2.40 ± 0.07	2.47 ± 0.09	2.66	.040	0.950 [0.301, 1.574]	Moderate
COD left (s)	2.49 ± 0.11	2.50 ± 0.10	0.32	.702	0.105 [-0.423, 0.628]	Trivial
1RM (kg)	149 ± 17.1	156 ± 31.0	5.08	.393	0.236 [-0.300, 0.763]	Small
Kicking (km/h)	96.5 ± 7.59	101 ± 6.46	5.32	<.001	1.458 [0.682, 2.208]	Large

Note. M = mean; SD = standard deviation; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; CI = confidence interval. Cohen's d = standardised effect size for paired samples. Effect-size magnitude was interpreted using the absolute value of Cohen's d: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥2.00).



Note. Bars represent group mean values for the First and Second Phases, while individual data points connected by lines represent each player's paired observations across the two assessment periods. Percentage change (Δ%), p values, and Cohen's d effect sizes with qualitative magnitude are reported for each variable. For time-based tests (T10, T30, and COD), negative percentage changes indicate faster performance, whereas positive changes indicate slower performance. Detailed descriptive statistics and 95% confidence intervals for Cohen's d are presented in Table 1.

Figure 2. Individual within-player seasonal changes in physical fitness and body-composition variables in U21 players.



Note. Bars represent group mean values for the First and Second Phases, while individual data points connected by lines represent each player's paired observations across the two assessment periods. Percentage change (Δ), p values, and Cohen's d effect sizes with qualitative magnitude are reported for each variable. For time-based tests (T10, T30, and COD), negative percentage changes indicate faster performance, whereas positive changes indicate slower performance. Detailed descriptive statistics and 95% confidence intervals for Cohen's d are presented in Table 2.

Figure 3. Individual within-player seasonal changes in physical fitness and body-composition variables in U18 players.

Individual paired trajectories further illustrated the within-player variability underlying the group-level seasonal changes in both categories (Figures 2 and 3). In U21 players, improvements were generally observed in CMJ, T30, kicking velocity, muscle mass, fat mass, and the sum of 6 skinfolds, whereas VO_{2max} and 1RM showed comparatively stable group-level responses and T10 performance declined. A broadly similar pattern was observed in U18 players, although individual variability was evident across several variables, particularly 1RM and change-of-direction performance. These individual trajectories support the interpretation that physical qualities did not follow a uniform seasonal pattern across players or performance domains.

Table 3 presents the correlations between physical fitness, body composition, and external match-load variables in the U21 category. CMJ was positively associated with PS ($r = .418$, $p < .01$), whereas T30 was negatively correlated with PS ($r = -.633$, $p < .01$), SPRINT ($r = -.358$, $p < .05$), and NSPRINT ($r = -.346$, $p < .05$). No other statistically significant correlations were identified between physical fitness, body composition, and external match-load variables.

Table 3. Correlations between physical fitness, body composition, and external match load variables during official competition in U21 players.

	TD	ACC	DEC	PS	PL	HSR	SPRINT	NSPRINT
CMJ (cm)	-.108	.125	-.093	.418**	-.256	.058	.158	.176
VO _{2max} (ml·kg ⁻¹ ·min ⁻¹)	.239	.039	.135	-.293	.226	-.044	-.208	-.191
T30 (s)	.176	-.088	.069	-.633**	.253	-.006	-.358*	-.346*
T10 (s)	.046	-.195	-.064	-.286	-.023	.022	-.121	-.147
COD right (s)	-.263	-.304	-.123	-.239	-.304	-.021	-.057	-.036
COD left (s)	-.182	-.320	-.061	.019	-.309	.220	.084	.067
1RM (kg)	-.136	.154	.022	.145	.070	.235	.032	.030
Kicking (km/h)	-.081	-.541	-.475	-.150	-.22	.351	-.187	-.150
%MM	.288	.066	.033	.142	.345	-.061	.038	.020
%FM	-.270	-.222	-.209	-.149	-.362	.238	-.134	-.106
6skf (mm)	-.164	-.225	-.230	-.325	-.170	.316	-.353	-.325

Note. CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; TD = total distance; ACC = accelerations; DEC = decelerations; PS = peak speed; PL = player load; HSR = high-speed running; SPRINT = sprint distance; NSPRINT = number of sprints. ** $p < .01$; * $p < .05$ (two-tailed).

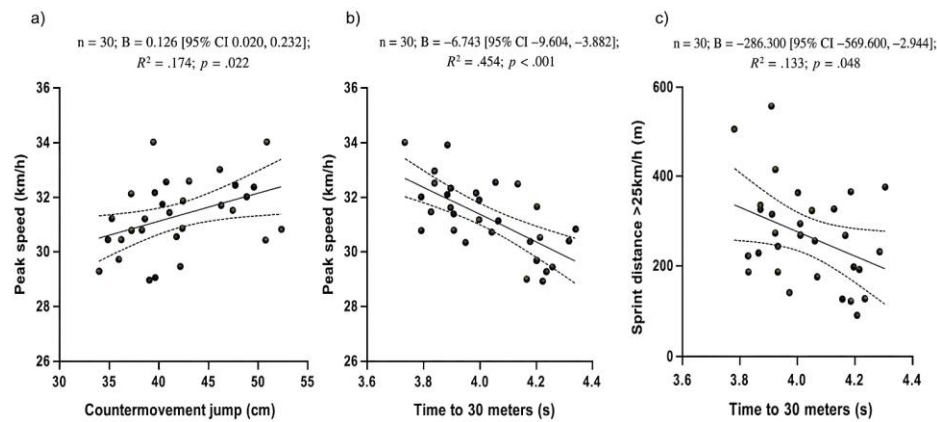
Table 4 presents the correlations between physical fitness, body composition, and external match-load variables during official competition in U18 players. CMJ was negatively associated with PL ($r = -.536$, $p < .01$) and positively associated with SPRINT ($r = .406$, $p < .05$) and NSPRINT ($r = .454$, $p < .05$). VO_{2max} was positively associated with TD ($r = .528$, $p < .01$). T30 was positively associated with PL ($r = .398$, $p < .05$) and negatively associated with SPRINT ($r = -.396$, $p < .05$) and NSPRINT ($r = -.405$, $p < .05$). In addition, 1RM was positively associated with PS ($r = .477$, $p < .05$), whereas kicking velocity was negatively associated with PS ($r = -.468$, $p < .05$). Finally, 6skf was negatively associated with PS ($r = -.454$, $p < .05$), SPRINT ($r = -.514$, $p < .01$), and NSPRINT ($r = -.500$, $p < .01$). No other statistically significant associations were identified.

Table 4. Correlations between physical fitness, body composition, and external match load variables during official competition in U18 players.

	TD (m)	ACC	DEC	PS	PL	HSR	SPRINT	NSPRINT
CMJ (cm)	-.278	-.088	-.011	.312	-.536**	-.017	.406*	.454*
VO _{2max} (ml·kg ⁻¹ ·min ⁻¹)	.528**	.134	.228	.193	.266	.262	-.042	-.066
T30 (s)	.165	.196	.088	-.348	.398*	.116	-.396*	-.405*
T10 (s)	.297	.096	.209	-.215	.110	-.359	-.061	-.056
COD right (s)	.160	.295	.263	.063	.010	-.302	.323	.338
COD left (s)	.048	.337	.364	.123	.091	.054	.214	.302
1RM (kg)	-.116	.037	-.172	.477*	-.258	-.123	.241	.278
Kicking (km/h)	.120	-.057	-.366	-.468*	-.289	-.276	-.278	-.294
%MM	-.058	-.040	.023	.125	-.186	-.082	.311	.265
%FM	.016	-.060	-.242	-.261	-.015	.050	-.326	-.340
6SKF (mm)	.104	-.374	-.335	-.454*	.063	-.025	-.514**	-.500**

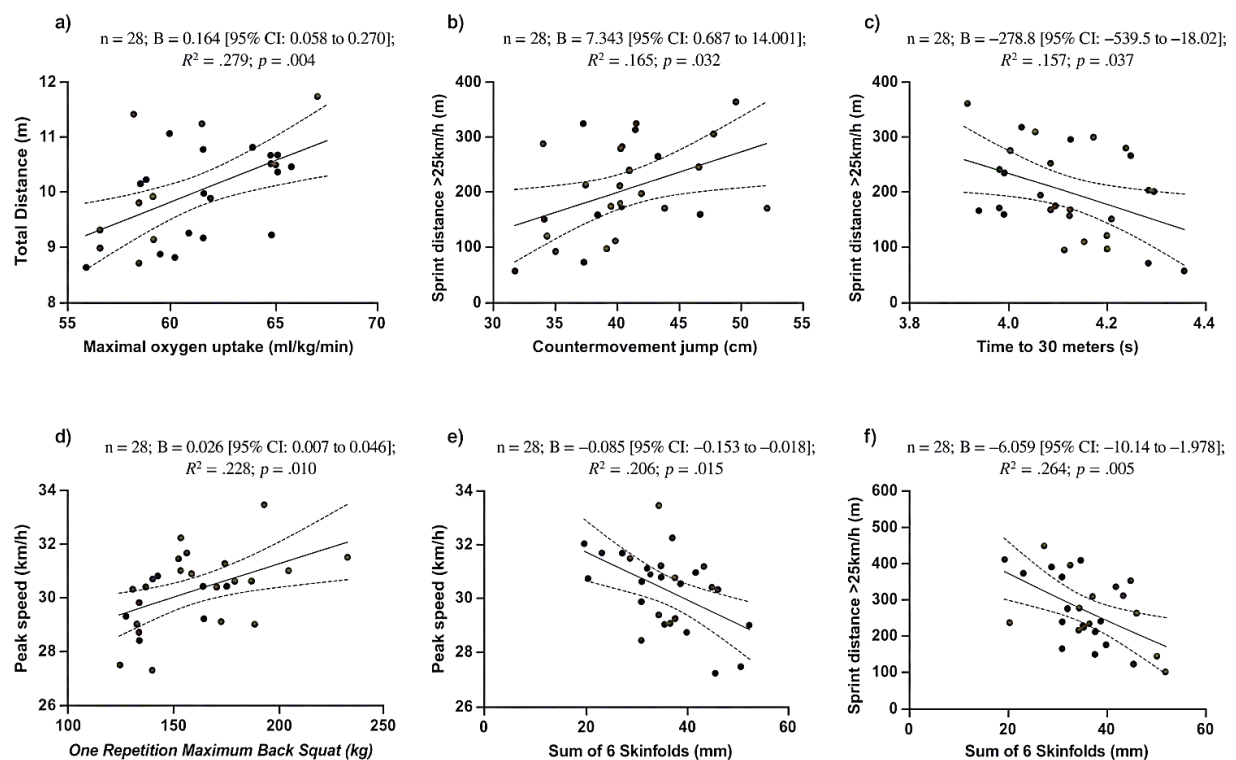
Note. Abbreviations: CMJ = countermovement jump; VO_{2max} = maximal oxygen uptake; T30 = 30-m sprint time; T10 = 10-m sprint time; COD = change of direction; 1RM = one-repetition maximum; MM = muscle mass; FM = fat mass; 6SKF = sum of six skinfolds; TD = total distance; ACC = accelerations; DEC = decelerations; PS = peak speed; PL = player load; HSR = high-speed running; SPRINT = sprint distance; NSPRINT = number of sprints. ** $p < .01$; * $p < .05$ (two-tailed).

Figures 4 and 5 present scatterplots of the significant associations explored using simple linear regression analyses in U21 and U18 players, respectively.



Note. (a) Countermovement jump with peak speed; (b) time to 30 meters with peak speed; and (c) time to 30 meters with sprint distance. Solid lines represent the fitted linear regression, while dashed lines represent the 95% confidence intervals. Each panel reports the number of player-phase observations (n), the unstandardized regression coefficient (B) with its 95% confidence interval (95% CI), the coefficient of determination (R^2), and the exact p value.

Figure 4. Significant simple linear regressions between physical fitness and external match-load variables in U21 football players.



Note. (a) Maximal oxygen uptake with total distance; (b) countermovement jump with sprint distance; (c) time to 30 meters with sprint distance; (d) one-repetition maximum back squat with peak speed; (e) sum of 6 skinfolds with peak speed; and (f) sum of 6 skinfolds with sprint distance. Solid lines represent the fitted linear regression, while dashed lines represent the 95% confidence intervals. Each panel reports the number of player-phase observations (n), the unstandardized regression coefficient (B) with its 95% confidence interval (95% CI), the coefficient of determination (R^2), and the exact p value.

Figure 5. Significant simple linear regressions between physical fitness, body composition, and external match-load variables in U18 football players.

To provide an integrated overview of the observed relationships, Table 5 summarizes the exploratory coupling patterns between physical-profile domains and external match-load expression across U18 and U21 players.

Table 5. Integrative summary of exploratory coupling patterns between physical-profile domains and external match-load expression in U18 and U21 players.

Physical-profile domain	Representative measure	U18 external match-load expression	U21 external match-load expression	Integrated interpretation
Aerobic fitness	VO _{2max}	↑ Total distance	No significant associations	Aerobic fitness showed a specific association with locomotor volume in U18 players.
Neuromuscular performance	CMJ	↑ Sprint exposure	↑ Peak speed	Neuromuscular performance was associated with high-intensity match expression, although the specific external-load outcome differed by age category.
Speed performance	T30	↑ Sprint exposure	↑ Peak speed and sprint exposure	Sprint performance showed the most consistent coupling with speed-related match demands across both categories.
Maximal strength	1RM back squat	↑ Peak speed	No significant associations	Maximal strength showed a category-specific association with peak-speed expression in U18 players.
Adiposity	Sum of 6 skinfolds	↓ Peak speed and sprint exposure	No significant associations	Greater adiposity was negatively associated with high-intensity match expression in U18 players.

Note. ↑ and ↓ indicate the direction of statistically significant associations. The table provides an integrative summary of representative exploratory associations rather than evidence of causal, predictive, or statistically confirmed between-category differences. Playing position, biological maturation, and match context should be considered potential moderators requiring further investigation.

DISCUSSION

The aim of the present study was to examine seasonal changes in body composition and physical fitness, as well as to explore the relationships between these variables and external match load during official competition in U18 and U21 football players. The main findings indicate that both categories demonstrated significant improvements in neuromuscular performance and body composition variables between the First Phase and the Second Phase. Furthermore, exploratory analyses revealed age-category-specific patterns in the coupling between physical profiles and external match-load expression, with a greater number of nominally significant associations observed in U18 players. These findings reinforce the need for integrated monitoring approaches in youth football, where the interaction between physical, anthropometric, and contextual factors contributes to competitive performance (Villaseca-Vicuña, Molina-Sotomayor, et al., 2021; Villaseca-Vicuña, Otero-Saborido, et al., 2021).

When considered collectively, the longitudinal findings indicate that the assessed physical qualities did not follow a uniform trajectory across the observation period. In both U18 and U21 players, improvements in body-composition indicators, CMJ, T30, and kicking velocity occurred alongside relatively stable aerobic fitness and maximal strength, whereas T10 performance declined. This pattern highlights the specificity of seasonal changes across different physical domains during the later stages of academy development, rather

than a homogeneous improvement in overall physical fitness. Such differentiated trajectories are consistent with the multidimensional nature of youth physical development, in which neuromuscular, speed, strength, aerobic, and body-composition characteristics may evolve differently according to biological development and accumulated training and competitive exposure (Lloyd et al., 2015; Moran et al., 2018). Importantly, although the typical weekly microcycle and competition density were documented in the present study, the specific internal and external training dose received by each player was not quantified. Therefore, the observed changes should be interpreted as seasonal trajectories rather than adaptations attributable to particular training stimuli.

In the U21 category, significant improvements were observed in body composition and neuromuscular performance, including increases in %MM (+1.89%; $p < .001$; ES = 1.685), reductions in %FM (-7.74%; $p < .001$; ES = 1.543) and 6skf (-10.2%; $p < .001$; ES = 1.227), alongside improvements in CMJ (+11.48%; $p < .001$; ES = 1.367) and T30 (-3.04%; $p < .001$; ES = 1.826). These findings are consistent with previous studies reporting positive adaptations throughout the competitive season in highly trained youth football players, particularly in neuromuscular capacities and body composition (Clemente et al., 2020). However, given the observational design of the present study, these changes cannot be attributed exclusively to the training programme and may reflect the combined influence of training exposure, competitive participation, biological development, and other contextual factors. Therefore, the absence of significant changes in VO_{2max} ($p = .789$) may suggest a ceiling effect or stabilisation of aerobic fitness during the competitive season, which has previously been reported in environments where training is predominantly focused on tactical and competitive demands (Malone et al., 2017). Moreover, the decline in T10 (+3.81%; $p = .005$) indicates a reduction in short-distance acceleration performance across the competitive season. Potential explanations may include differences in acceleration-specific training exposure, competitive demands, or other contextual factors; however, these mechanisms were not directly assessed in the present study and should therefore be considered hypothetical (Gualtieri et al., 2023).

A similar pattern was observed in the U18 category, with significant increases in %MM (+1.89%; $p = .014$), reductions in %FM (-4.96%; $p = .003$) and 6skf (-11.2%; $p < .001$), together with improvements in CMJ, T30, and KV. However, T10 and COD Right showed significant declines, indicating reduced acceleration and change-of-direction performance. These findings are in agreement with the literature identifying adolescence as a critical period for the development of physical capacities, influenced by the interaction between biological maturation and training exposure (Lloyd et al., 2015; Moran et al., 2018). Nevertheless, the deterioration in COD Right (+2.66%; $p = .040$) indicates a reduction in right-sided change-of-direction performance across the competitive season. Although factors such as accumulated fatigue, training exposure, or sport-specific stimulus could potentially contribute to this pattern, these mechanisms were not directly assessed and should therefore be considered hypothetical. Previous studies have highlighted that COD depends not only on strength but also on technical, coordinative, and neuromuscular control factors, which may not develop optimally without targeted training interventions (Dos'Santos et al., 2018).

In the U21 category, the correlational analysis revealed that neuromuscular and speed-related variables were the principal physical characteristics associated with external match load. CMJ was positively related to PS ($r = .418$; $p < .01$), whereas T30 was negatively associated with PS ($r = -.633$; $p < .01$), SPRINT ($r = -.358$; $p < .05$), and NSPRINT ($r = -.346$; $p < .05$). These findings suggest that greater lower-limb neuromuscular performance and faster 30-m sprint performance may be associated with the ability to reach higher peak speeds and accumulate greater sprint-related demands during competition, supporting previous evidence highlighting the relevance of power and sprint capacity in football (Djaoui et al., 2017). In contrast, VO_{2max} and body composition variables were not significantly associated with the external match-load variables

examined in U21 players. Therefore, within this category, the observed relationships were primarily concentrated in neuromuscular and sprint-related performance characteristics.

Exploratory correlation analyses revealed a greater number of nominally significant associations in the U18 category; however, given the number of bivariate comparisons performed, these findings should be interpreted cautiously and considered hypothesis-generating. Notably, CMJ was positively associated with SPRINT and NSPRINT and negatively associated with PL, while VO_{2max} was positively associated with TD. T30 was positively associated with PL and negatively associated with SPRINT and NSPRINT, whereas 1RM was positively associated with PS. The greater number of associations observed in U18 players should be interpreted as an exploratory pattern rather than evidence that physical capacities exert a stronger influence on competitive performance in younger players. As no formal between-category comparison of correlation coefficients or regression slopes was performed, differences in the number of significant associations cannot establish developmental differentiation between U18 and U21 players. Furthermore, 6skf was negatively associated with selected high-intensity external match-load variables, including PS, SPRINT, and NSPRINT, supporting the potential relevance of adiposity-related characteristics to high-intensity match-load expression (Rios-Limas et al., 2025). The greater number of associations observed in U18 players may reflect differences in physical variability, sample characteristics, or developmental heterogeneity; however, these potential explanations remain speculative and require confirmation through formal between-category analyses (Moran et al., 2018).

When the associations are considered within an integrated monitoring framework (Table 5), distinct exploratory coupling patterns emerge between physical-profile domains and external match-load expression across the two age categories. Speed-related and neuromuscular qualities showed the most consistent relationships with high-intensity match demands across both groups, supporting the relevance of sprint and neuromuscular capacities within the multidimensional physical demands of football (Clemente et al., 2019; Villaseca-Vicuña, Molina-Sotomayor, et al., 2021). In U18 players, this pattern extended to additional physical domains, with aerobic fitness associated with total locomotor volume, maximal strength with peak-speed expression, and greater adiposity with lower peak-speed and sprint exposure. These findings are consistent with the multidimensional nature of physical development during adolescence, where training exposure and biological maturation interact with the development and expression of different physical capacities (Lloyd et al., 2015; Moran et al., 2018). In contrast, significant associations in U21 players were concentrated primarily within neuromuscular and speed-related domains. Importantly, these patterns should not be interpreted as evidence of stronger physical determinants in U18 players or reduced physical relevance in U21 players, because between-category differences in association strength were not formally tested. Rather, they provide preliminary evidence that the coupling between physical profiles and external match-load expression may be age-category specific. Playing position, biological maturation, and match context may further influence these relationships and should therefore be incorporated into future multilevel and multi-club investigations (Lloyd et al., 2015; Villaseca-Vicuña, Otero-Saborido, et al., 2021). The present findings also extend the geographical context of the available academy-football literature by providing longitudinal and match-derived evidence from a South American professional academy. While several of the observed patterns are broadly consistent with previous research from European youth-development environments, the present results should be interpreted within the specific training, competitive, and developmental context of this academy. Accordingly, the potentially transferable principle is not the magnitude of the individual changes or associations observed in this cohort, but rather the value of integrating longitudinal physical profiling with match-derived external-load monitoring to characterize player development. Whether the specific seasonal trajectories and physical-match-load coupling patterns observed here generalize across academy systems requires further investigation.

Limitations

First, the observational design precludes the establishment of causal relationships. Second, the sample was drawn from a single South American professional football academy; therefore, the observed seasonal trajectories and physical-match-load associations should be considered context-specific rather than representative of youth football more broadly. Multi-club studies across different academy and geographical contexts are required to examine the transferability of these findings, incorporating biological maturation, playing position, and relevant match-context variables as potential sources of variation. Furthermore, biological maturation status was not assessed, despite being a key determinant of physical development and performance in youth football players (Lloyd et al., 2015). Additionally, although the association analyses were based on phase-specific rather than individual match observations, each player contributed data from two competitive phases. Therefore, the potential within-player dependency of these repeated seasonal observations should be considered when interpreting the correlational findings. Future studies with larger samples should examine these relationships using multilevel approaches. Furthermore, the exploratory association analyses involved multiple bivariate comparisons without formal adjustment for multiplicity, which may increase the probability of type I error. Therefore, particularly small-to-moderate associations close to the conventional significance threshold should be interpreted cautiously and considered hypothesis-generating. Future studies with larger samples should confirm these relationships using prespecified hypotheses and appropriate multiplicity-control procedures. In addition, the association and simple regression analyses performed in the present study were not designed to establish predictive validity or identify performance thresholds. Future studies with larger samples should develop cross-validated multivariable models to determine whether physical-fitness and body-composition markers provide incremental predictive value for external match-load outcomes beyond age category, playing position, playing time, and contextual match variables. Although the typical weekly microcycle structure and competition density were documented, individual session-level internal and external training loads were not quantified within the present analysis. Therefore, the observed seasonal changes cannot be attributed to specific training stimuli or training-load characteristics. Future studies should quantify individual accumulated training and competition exposure to determine how specific loading patterns may contribute to the distinct seasonal trajectories observed across physical qualities. Finally, contextual variables such as playing position, quality of opposition, and match location were not controlled, despite their recognised influence on external match load (Villaseca-Vicuña, Merino-Muñoz, et al., 2026).

The findings highlight the importance of integrating body composition, physical fitness, and external load monitoring within youth football development programmes. Variables related to countermovement jump and sprint performance showed associations with selected high-intensity external match-load outcomes, suggesting that these assessments may serve as potentially informative monitoring markers when interpreted alongside match-derived external-load data. However, these associations should not be interpreted as evidence of predictive validity, and the present findings do not establish performance thresholds or demonstrate that these tests independently predict competitive match demands. Likewise, maintaining optimal body composition appears fundamental for maximising physical fitness during competition. The exploratory pattern of associations observed across U18 and U21 players highlights the potential value of considering competitive category when interpreting the relationships between physical characteristics and external match load, although formal between-category comparisons are required before developmental differences can be established. Consequently, integrated monitoring systems are recommended to facilitate individualised training prescription and optimise player development in the short, medium, and long term (Lloyd et al., 2015).

CONCLUSION

In conclusion, this study provides context-specific evidence from a South American professional football academy regarding seasonal changes in physical fitness and body composition and their associations with external match-load expression in U18 and U21 players. The findings indicate that different physical qualities followed distinct seasonal trajectories and showed exploratory age-category-specific coupling patterns with competitive external-load outcomes. Rather than representing predictive indicators of competitive performance, the observed associations support the potential value of selected physical assessments as informative monitoring markers when interpreted alongside match-derived external-load data. Overall, integrating longitudinal physical profiling with competition monitoring may provide a useful framework for supporting player development during the later stages of academy football. However, the magnitude and specific patterns observed in this cohort should not be generalised to youth football more broadly, and multi-club replication across different geographical and developmental contexts is required.

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:

Conceptualization: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz, Jorge Pérez-Contreras. Methodology: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz, Jorge Pérez-Contreras, Guillermo Cortés-Roco. Formal analysis: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz. Investigation: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz, Guillermo Cortés-Roco, Marcelo Muñoz. Data curation: Rodrigo Villaseca-Vicuña, Pablo Merino-Muñoz. Writing – original draft: Rodrigo Villaseca-Vicuña. Writing – review & editing: Pablo Merino-Muñoz, Rodrigo Yáñez-Sepúlveda, Guillermo Cortés-Roco, Marcelo Muñoz, Jorge Pérez-Contreras. Supervision: Jorge Pérez-Contreras.

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.

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