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Research article

Effects of Different Training Load Parameters on Physical Performance Adaptation in Soccer Players: How Complex Intensities Influence The Magnitude of Adaptations

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Abstract
The aim of this study was to examine how physiological, locomotor, and mechanical load parameters contribute to variations in aerobic, anaerobic, and neuromuscular adaptations in male soccer players. A 12-week cohort study was conducted involving 41 male under-17 soccer players (16.4 ± 0.5 years old). All training sessions and matches were monitored using heart rate (HR) monitors, ratings of perceived exertion (RPE), and a global positioning system (GPS). The following variables were recorded daily: training impulse (TRIMP), session-RPE, total distance, high speed running (14.0 to 19.9 km/h, HSR), and very high speed running (>20 km/h, VHSR), and the number of accelerations and decelerations. Physical fitness was assessed twice - at baseline and after the 12-week intervention. The assessments included aerobic capacity via the Yo-Yo Intermittent Recovery Test (YYIRT), anaerobic capacity via the mean sprint time at Running-Based Anaerobic Sprint Test (RSAmean), muscle power using the Countermovement Jump (CMJ), and sprint performance measured in a 30-meter sprint. Simple linear regressions showed that both accumulated session-RPE ($R^2 = 0.446$, $\beta = 0.668$, $p < 0.001$) and accumulated TRIMP ($R^2 = 0.417$, $\beta = 0.646$, $p < 0.001$) were significant positive predictors of YYIRT delta, although explain less than half of variance. A multiple regression analysis revealed that accumulated VHSR significantly predicted RSAmean delta, indicating that higher VHSR values are associated with smaller and improved RSAmean ($B = -0.003$, $p = 0.002$), while HSR was not a significant predictor ($p = 0.291$). These findings suggest that internal load measures (session-RPE, TRIMP) are more strongly associated with aerobic adaptations, while specific external load metrics (e.g., VHSR) better explain RSA changes, highlighting the importance of modifying load monitoring strategies to the specific physiological adaptations targeted. Incorporating individualized load management based on these measures may help maximize performance improvements in practical contexts.

Key words: Effort, sports training, football, training load, physical fitness.

Introduction

Training load is a multidimensional construct representing the amount of physical training an athlete completes or experiences (McLaren et al., 2022a). It comprises two subconstructs: external load (performance outputs) and internal load (physiological and biomechanical stresses) (Impellizzeri et al., 2019). These concepts align with epidemiological terms of exposure and dose (Impellizzeri et al., 2023). While training load is widely used in sports science, its validity as a measure of training dose has been questioned (Passfield et al., 2022). Some researchers argue that common training load metrics may not accurately represent training dose and that exercise duration confounds calculations (Passfield et al., 2022). However, others contend that this critique addresses the metrics used to quantify training load rather than the concept itself (McLaren et al., 2022b). To optimize training, measures of exposure must reflect the mediating mechanisms that directly cause changes in primary outcomes, making it essential to distinguish causal dose-response relationships - where altering exposure leads to predictable outcome changes - from non-causal associations that do not imply direct influence (Impellizzeri et al., 2023).

Research on training load shows a mediating effect in physical fitness adaptations in soccer players. Higher training volumes and perceived loads are associated with greater improvements in aerobic fitness (Manzi et al., 2013; Gil-Rey et al., 2015). However, excessive accumulation of training volume and high perception of leg muscular effort can impair improvements in physical fitness attributes (Los Arcos et al., 2015). The midweek training sessions typically have the highest training load, while sessions immediately before and after matches have lower loads for tapering and recovery (Silva et al., 2023). Individual training impulse (TRIMPi) shows strong correlations with changes in aerobic fitness variables, with a weekly TRIMPi > 500 AU necessary for improvements in premiership soccer players during preseason (Manzi et al., 2013).

Also, external training load monitoring may play a role in optimizing physical fitness adaptations in soccer players. A six-week preparatory training program for youth soccer players demonstrated significant improvements in physical performance indicators, with correlations found between external load parameters and both objective and subjective internal load measures (Lechner et al., 2023). External load metrics, particularly total distance and high-speed running, showed stronger associations with changes in aerobic fitness compared to internal load measures (Papadakis et al., 2020). On the other hand, a study conducted on professional soccer players revealed that aerobic performance and isokinetic strength were only weakly correlated with GPS-based measures, preventing the establishment of a direct causal relationship between external load and physical adaptations (Clemente et al., 2019). The use of ratios combining internal and external loads, such as total distance (TD):iTRIMP and high intensity distance (HID):iTRIMP, has demonstrated significant correlations with fitness parameters like Velocity at Lactate Threshold

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and Velocity at Onset of Blood Lactate Accumulation (Akubat et al., 2014). Since current research are primarily correlational, they cannot confirm causation; therefore, future research should employ experimental or longitudinal approaches to clarify causal links between training load and physical fitness adaptations. Moreover, the contrasting findings may be related to the context of the intervention - since most studies are conducted within a single team (Manzi et al., 2013; Gil-Rey et al., 2015) - where the specific training process can introduce greater bias in the observed trends and relationships of adaptations.

Building on the current understanding of training load as a complex construct, there is a clear rationale for conducting research that integrates both internal and external load measures to investigate their combined influence on performance adaptations in soccer players (Akubat et al., 2014). While previous studies have predominantly established separate relationships between internal or external load and specific fitness outcomes (Jaspers et al., 2017), a more comprehensive approach may uncover deeper insights into how these loads interact to mediate improvements in key physical attributes as aerobic, anaerobic, sprint, and jump performance. Given the complex and multifactorial nature of physical fitness development in soccer, combining internal load indicators with external load parameters like total distance, high-speed running, or accelerations may provide a more accurate representation of the true training dose. This integration could help clarify the dose-response relationships underpinning performance adaptations, especially considering that certain measures may better reflect the physiological demands of training than others. Moreover, understanding how the interplay between internal and external loads influences distinct performance domains could lead to more individualized and effective training strategies, optimizing performance. This relevance may be even greater in the context of youth players, as research on training load parameters in this group is less extensive compared to that conducted on adults. To address these limitations the aim of this study was to examine how heart rate (HR), ratings of perceived exertion (RPE), and distances covered at various speeds contribute to variations in aerobic, anaerobic, and neuromuscular adaptations in male soccer players.

Methods

Study design and context

This study employed a 12-week cohort design to investigate the physical fitness and training load of two amateur, regional-level under-17 football teams. This approach allowed for the observation of adaptation processes in an ecological environment, which would be difficult to control in an experimental setting with different training methodologies in a sports performance scenario. Data collection occurred at two distinct time points: baseline, coinciding with the beginning of the pre-season phase, and after 12 weeks, representing the early season. Physical fitness assessments were conducted at both time points to evaluate changes over the intervention period. Throughout the 12-week cohort, all training sessions and matches were monitored to quantify internal load, using both heart rate (HR)-derived measures and the rate of perceived exertion (RPE), and external load, captured via global positioning system (GPS) technology. The selection of these two teams was based on convenience sampling, determined by their accessibility and willingness to participate in the research protocol within the given timeframe. For this descriptive study, researchers had no direct involvement in the teams' training plans. Instead, the evolution of the players' physical fitness, as well as their training and match loads, were monitored throughout the 12-week period.

Participants

An a priori sample size estimation was conducted using G*Power software (Version 3.1; Universität Düsseldorf, Germany) to determine the minimum required sample size for this correlational study. The analysis was performed to ensure adequate statistical power to detect a significant relationship between training load variables and magnitude of adaptations in physical fitness. The statistical test was specified as Correlation: Bivariate normal model. An 'a priori' power analysis was selected to compute the necessary sample size. For this analysis, we specified a two-tailed test, given the absence of a directional hypothesis regarding the relationship between the variables. A significance level (α) of 0.05 was adopted. Based on magnitude of correlation found in a previous study (Gil-Rey et al., 2015), we estimated a Effect size (ρ) of 0.707. With the desired power (1-β) set at 0.95, the G*Power analysis indicated a minimum required sample size of N = 19.

Participants were eligible for inclusion in the study if they were male soccer players aged 16 to 17 years, had a minimum of three years of playing experience, were present during all assessment sessions, being outfield players, and did not miss more than 10% of training sessions during the observational period. Potential participants were excluded if they had experienced any musculoskeletal injuries within the three months prior to the study that could limit their ability to participate in physical fitness testing or training/match monitoring and if they were goalkeepers.

Two under-17 soccer teams from a regional amateur league were recruited using convenience sampling. Team coaches were first contacted and provided with detailed information about the study's purpose, procedures, and potential risks and benefits. After obtaining consent from the coaches, informational meetings were held with the players and their parents or guardians to further explain the study. Written informed consent was obtained from the parents or guardians, and assent was obtained from the players prior to participation in any study-related activities. The study adhered to the ethical guidelines outlined in the Declaration of Helsinki and was approved by the Geely University of China Ethics Committee under approval code NO.20250220.

After recruitment, 41 male under-17 soccer players (age: 16.4 ± 0.5 years; playing experience: 4.2 ± 1.1 years; body mass: 59.4 ± 2.9 kg; height: 171.7 ± 3.7 cm) voluntarily participated in this study. They followed a regular training schedule consisting of four sessions per week, each lasting approximately 100 minutes. All participants competed at the regional level and were involved in the same competitive tier.

Procedures

At baseline and after 12 weeks, players were evaluated on a single day during the first training session of the week, following 48 hours of rest. Assessments took place in the afternoon, around 4:00 p.m., beginning in a climate-controlled room and continuing on a synthetic turf field.

The evaluation session began with anthropometric measurements, followed by a general and standardized warm-up based on the FIFA 11+ protocol. Players then completed a consistent sequence of physical performance tests, starting with the countermovement jump (CMJ), followed by a 30-meter sprint test. Next, participants performed the Repeated Sprint ability test (RSA), and finally, the Yo-Yo Intermittent Recovery Test Level 1 (YYIRT1). A 5-minute rest period was provided between each test. Environmental conditions during the field-based assessments were 24.2 ± 1.7°C with 57.2 ± 3.1% relative humidity.

Throughout all training sessions and matches between the two evaluations, players were monitored using heart rate monitors, the rating of perceived exertion (RPE) scale, and GPS technology. Training sessions were regularly held on Mondays, Tuesdays, Thursdays, and Fridays. Mondays were dedicated to recovery and tactical/technical drills, while Tuesdays focused more on strength and plyometric training, often incorporating small-sided games. On Thursdays, the emphasis was on cardiorespiratory conditioning and endurance, followed by specific analytical drills and a friendly match. Fridays were designed to reduce training volume while maintaining intensity through speed and velocity-focused analytical drills. While HR and GPS data were monitored throughout the entire session, the RPE was assessed approximately 20 minutes after the session ended.

Outcomes and measures

Countermovement jump (CMJ)

Lower body power was assessed using the countermovement jump (CMJ) test. Participants performed the CMJ on a stable surface, and jump height was measured using the MyJump 2 app which was found to be valid and reliable to measure vertical jump height in comparison to photoelectric cell system (Bogataj et al., 2020). To ensure the reliability of the observer conducting the process, a pilot test was performed with ten participants (not included in the main sample). The observer analyzed the same videos at two different time points, separated by a 15-day interval. The Intraclass Correlation Coefficient was calculated, yielding a value of 0.92, indicating excellent intra-rater reliability. Participants began standing upright, then performed a rapid countermovement, flexing their knees and hips before immediately extending them to jump vertically. They were instructed to keep their hands on their hips throughout the entire movement to isolate lower body power. Two successful trials were performed, and the average jump height (cm) was used for analysis.

30-m sprint performance

Sprint performance was assessed using the 30-meter sprint test. Participants started from a standing position with their preferred front foot placed at the starting line. Sprint time was measured using the Photo Finish mobile application (Marco-Contreras et al., 2024). The application was set up at the starting line, the 5-meter mark (start/finish line), and the 5-meter turning line. The reliability and validity of the Photo Finish mobile application have been previously established in comparison to photocells (Marco-Contreras et al., 2024). Two successful trials were performed, and the average time was used for analysis.

Repeated sprint ability (RSA)

The ability to perform repeated sprints (RSA) was evaluated using a protocol of 6 shuttle sprints over 40 meters (20 meters out and 20 meters back), with 20 seconds of passive recovery between each sprint (Rampinini et al., 2009). This test assessed the capacity to maintain sprint performance during repeated efforts, along with change-of-direction ability (Rampinini et al., 2009). Participants initiated each sprint from a starting line, sprinted 20 meters to touch a cone, and then sprinted back to the starting line. A 20-second passive recovery period was implemented before the commencement of the subsequent sprint (Rampinini et al., 2009). Participants were required to position themselves at the starting line 5 seconds prior to each sprint, awaiting the start signal (Rampinini et al., 2009). The mean RSA (s) was calculated as the average time of all sprints performed during the test.

The Yo-Yo Intermittent recovery test level 1 (YYIRT)

The Yo-Yo Intermittent Recovery Test Level 1 (YYIR1) was used to assess aerobic endurance and the capacity for intermittent exercise. The test involved repeated 2 x 20-meter shuttle runs. Participants began running at 10 km/h, and the pace was increased by 0.5 km/h for each subsequent level, guided by audio signals. A 10-second active recovery period separated each shuttle. The test continued until participants failed to maintain the required pace on two consecutive occasions. The total distance covered before failure, measured in meters, was the primary outcome, reflecting the participant's ability to perform high-intensity intermittent exercise.

Rating of Perceived Exertion (RPE)

Rate of Perceived Exertion (RPE) was used to quantify the participants' subjective experience of exercise intensity. The CR-10 Borg scale was employed, a numerical scale ranging from 0 to 10, where 0 represents "rest" and 10 represents "maximal exertion" (Borg, 1982). Prior to the study, participants were familiarized with the CR-10 Borg scale through verbal explanation and practical examples. They were instructed on how to associate their feeling of exertion with the corresponding number on the scale. Participants were asked to rate their overall perception of effort for each training session and match within 20 minutes following its conclusion. Ratings were recorded using a paper-based survey. To calculate session-RPE (sRPE), the reported RPE value was multiplied by the total duration of the session (in minutes) (Foster et al., 2001). This sRPE value provides a measure of the overall internal training load.

Heart rate measures (HR)

Heart rate was monitored continuously during all training sessions and matches using Polar Bluetooth heart rate sensors (Polar Electro Oy, Finland). Data was recorded at 1 Hz. Maximal heart rate (HRmax) for each participant was determined from the Yo-Yo Intermittent Recovery Test Level 1 (YYIR1). The primary measure derived from the heart rate data was the Edwards's Training Impulse (Edwards's TRIMP) calculated using Edwards's formula, with HRmax as a personal constant. Edwards's TRIMP was calculated as: TRIMP = Σ (HR zone points x duration in zone), where: HR zone points are assigned as follows: Zone 1: 50 - 59% HRmax (1 point); Zone 2: 60 - 69% HRmax (2 points); Zone 3: 70 - 79% HRmax (3 points); Zone 4: 80 - 89% HRmax (4 points); and Zone 5: 90 - 100% HRmax (5 points). Duration in zone is the time in minutes spent in each heart rate zone. The TRIMP score is the sum of the products of heart rate zone points and the duration in that zone for the entire training session or match.

Global Positioning System (GPS)

Players' movement demands were monitored using the Polar Team Pro GPS system (Polar Electro Oy, Finland). Each player wore a GPS sensor, positioned in a vest, during all training sessions and matches. The Polar Team Pro system has verified acceptable validity and reliability in tracking distance and speed in team sports (Akyildiz et al., 2020). The following measures were obtained: total distance covered by each player (m), distance covered at high speed (HSR, 14.00 to 19.99 km/h) (m), and distance covered at very high speed (VHSR, > 20 km/h) (m). The measures were defined as direct calculations from the equipment, which do not allow for modifications.

Quantitative variables

For each participant, the accumulated training load over the 12-week intervention period was calculated for session-RPE, Edwards' TRIMP, total distance, high-speed running (HSR), and very high-speed running (VHSR) by summing the values of each parameter across all training sessions and matches. Changes in physical fitness were assessed by calculating delta values (post-intervention score minus pre-intervention score) for each fitness test (CMJ, 30-m sprint, YYIR1, and RSA), representing the magnitude of change in each outcome. The relationship between accumulated training load and changes in physical fitness was then analyzed to explore how the training load parameters were associated with the delta values of each fitness test.

Statistical procedures

The relationship between accumulated training load and changes in physical fitness was explored using multilinear regression. Players with missing heart rate or GPS data for specific training sessions were excluded from the calculation of accumulated training load for those sessions. Only complete data were used to compute training load parameters to ensure the accuracy of the regression models. Consequently, players with insufficient data across the observation period were excluded from analyses involving changes in physical fitness to maintain consistency and reliability of the results. Prior to the analysis, assumptions of linearity, independence of errors (using the Durbin-Watson statistic), homoscedasticity (using residual plots), and normality of errors (using histograms, Q-Q plots, and the Shapiro-Wilk test) were checked. Multicollinearity was assessed using the variance inflation factor (VIF), with values greater than 5 or 10 indicating high multicollinearity. For each fitness outcome, a separate multilinear regression model was performed, with the delta value as the dependent variable and the accumulated training load parameters as the independent variables. The models were run using SPSS statistical software (version 28.0, IBM, USA) with the significance level set at $p < 0.05$. The coefficient of determination (R^2), adjusted R^2, F-statistic, and t-tests were used to evaluate the models. In case of multicollinearity, highly correlated independent variables were removed or combined. For significant predictors, effect sizes were calculated using partial eta squared (ηp2) and interpreted as small (ηp2 = 0.01), medium (ηp2 = 0.06), or large (ηp2 = 0.14). To assess changes in physical fitness outcomes over the 12-week observation period, paired-samples t-tests were conducted comparing pre- and post-intervention measurements for each variable. The magnitude of any observed changes was evaluated using Cohen's d to determine the standardized effect size. The magnitude of differences for Cohen's d was interpreted as follows: values around 0.2 indicate a small effect, 0.5 a medium effect, and 0.8 or higher a large effect. Moreover, the Pearson correlation test was employed to examine the relationship between variables. The magnitude of the correlation was interpreted as follows: values between 0.1 and 0.3 were considered small, 0.3 to 0.5 moderate, and values above 0.5 large.

Results

Table 1 presents the baseline and post-12-week period variations in physical fitness variables. Significant improvements were observed in YYIRT ($t = 47.984$; $p < 0.001$; Cohen's d = 1.202, large effect size), 30-m sprint time ($t = 46.655$; $p < 0.001$; Cohen's d = 1.788, large effect size), RSAmean ($t = 95.426$; $p < 0.001$; Cohen's d = 1.645, large effect size), and CMJ ($t = 45.817$; $p < 0.001$; Cohen's d = 1.064, large effect size).

Over the 12-week observation period, the accumulated session-RPE was 40,179.3 ± 2,156.0 A.U., the accumulated TRIMP was 9,281.2 ± 537.4 A.U., the accumulated total distance was 291.3 ± 13.4 km, the accumulated HSR was 45.8 ± 3.8 km, and the accumulated VHSR was 15.6 ± 1.5 km.

Table 1. Baseline and post-12-week period variations in physical fitness variables.

YYIRT baseline (m)	YYIRT post (m)	YYIRT delta (m)	30-m sprint baseline (s)	30-m sprint post (s)	30-m sprint delta (s)	RSA mean baseline (s)	RSA mean post (s)	RSA mean delta (s)	CMJ baseline (cm)	CMJ post (cm)	CMJ delta (cm)
1398.1±127.3	1550.7±124.7	152.7±20.4	4.32±.05	4.22±.04	–.10±.01	7.70±.08	7.57±.08	–.13±.01	33.2±.7	34.0±.7	.8±.1

YYIRT: Yo-Yo Intermittent recovery test level 1; RSA: repeated sprint ability; CMJ: countermovement jump; Delta represents the absolute values post-baseline.

Table 2. Correlation (r, [95%Confidence intervals]) matrix between the delta (post-baseline) values for the physical fitness outcomes and the accumulated training load variables over the 12-week observation period.

	Acc. sRPE (A.U.)	Acc. TRIMP (A.U.)	Acc. TD (km)	Acc. HSR (km)	Acc. VHSR (km)
YYIRT delta (m)	r = 0.668 [0.447;0.807]; p < 0.001**	r = 0.646 [0.416;0.793]; p < 0.001**	r = -0.098 [-0.393;0.217]; p = 0.542	r = -0.001 [-0.308;0.307]; p = 0.996	r = -0.048 [-0.350;0.264]; p = 0.768
30-m sprint delta (s)	r = -0.100 [-0.395;0.215]; p = 0.533	r = -0.073 [-0.372;0.241]; p = 0.650	r = -0.062 [-0.362;0.251]; p = 0.702	r = -0.078 [-0.375;0.237]; p = 0.629	r = -0.210 [-0.484;0.107]; p = 0.187
RSAmean delta (s)	r = 0.060 [-0.253;0.360]; p = 0.709	r = 0.059 [-0.254;0.359]; p = 0.716	r = 0.202 [-0.115;0.478]; p = 0.206	r = -0.352 [-0.592;-0.045]; p = 0.024*	r = -0.550 [-0.730;-0.285]; p < 0.001**
CMJ delta (cm)	r = -0.050 [-0.351;0.263]; p = 0.758	r = -0.057 [-0.358;0.255]; p = 0.721	r = 0.198 [-0.119;0.475]; p = 0.214	r = 0.075 [-0.239;0.374]; p = 0.639	r = -0.091 [-0.387;0.224]; p = 0.572

YYIRT: Yo-Yo Intermittent recovery test level 1; RSA: repeated sprint ability; CMJ: countermovement jump; Acc.: accumulated over the 12 weeks; sRPE: session rating of perceived exertion; TRIMP: training impulse; TD: total distance; HSR: high-speed running; VHSR: very high speed running; Delta represents the absolute values post-baseline. *: significant correlations ($p < 0.05$); **: significant correlations ($p < 0.001$).

Table 2 presents the correlation matrix between the delta (post-baseline) values for the physical fitness outcomes and the accumulated training load variables over the 12-week observation period. The correlation analysis revealed a significant positive correlation between the change in YYIRT performance (YYIRT delta) and accumulated sessionRPE (r = 0.668, 95% CI [0.447, 0.807], large correlation, $p < 0.001$). Similarly, a significant positive correlation was observed between YYIRT delta and accumulated TRIMP (r = 0.646, 95% CI [0.416, 0.793], large correlation, p = 0.001). Furthermore, there was a significant negative correlation between the change in RSAmean and accumulated HSR (r = -0.352, 95% CI [-0.592, -0.045], moderate correlation, p = 0.024). The correlation analysis also revealed a significant negative correlation between the change in RSAmean and accumulated VHSR (r = -0.558, 95% CI [-0.735, -0.296], large correlation, $p < 0.001$).

A simple linear regression analysis was conducted to examine the relationship between accumulated sessionRPE and the YYIRT delta. The model explained a statistically significant proportion of the variance in the dependent variable ($R^2 = 0.446$, Adjusted $R^2 = 0.432$, $F_{(1,39)} = 31.448$, $p < 0.001$). The coefficient for accumulated sessionRPE was positive and statistically significant (B = 0.006, SE = 0.001, $t_{(39)} = 5.608$, $p < 0.001$). For every one-unit increase in accumulated session RPE, the dependent variable is predicted to increase by .006 units. The standardized beta coefficient (β = 0.668) suggests a moderately strong positive relationship between accumulated sessionRPE and the YYIRT delta. Figure 1a presents a scatterplot illustrating the relationship between accumulated session-RPE and the YYIRT delta. The figure illustrates a positive linear relationship between the YYIRT delta and accumulated session-RPE, with data points generally trending upward. This suggests that as the accumulated session-RPE increase, the YYIRT delta tends to increase as well.

Also, in a simple linear regression analysis examining the relationship between accumulated TRIMP and the YYIRTdelta, the model was statistically significant ($R^2 = 0.417$, Adjusted $R^2 = 0.402$, $F_{(1,39)} = 27.939$, $p < 0.001$). The coefficient for accumulated TRIMP was positive and statistically significant (B = 0.024, SE = 0.005, $t_{(39)} = 5.286$, $p < 0.001$). For every one-unit increase in accumulated TRIMP, the dependent variable is predicted to increase by 0.024 units. The standardized beta coefficient (β = .646) suggests a moderately strong positive relationship between accumulated TRIMP and the YYIRT delta. Figure 1b presents a scatterplot illustrating the relationship between accumulated TRIMP and the YYIRT delta. The figure illustrates a positive linear relationship between the YYIRT delta and accumulated TRIMP, with data points generally trending upward. This suggests that as the accumulated TRIMP increase, the YYIRT delta tends to increase as well.

A multiple linear regression analysis was conducted to examine the extent to which accumulated VHSR and accumulated HSR predicted RSAmean delta. The overall model was statistically significant ($R^2 = 0.322$, Adjusted $R^2 = .287$, $F_{(2,38)} = 9.041$, $p < 0.001$), indicating that these two predictors collectively accounted for a significant proportion of the variance in the dependent variable. Examination of the individual predictors revealed that accumulated VHSR had a statistically significant negative relationship with RSAmean delta (B = -0.003, SE = 0.001, $t_{(38)} = -3.340$, p=0.002). In contrast, the relationship between accumulated HSR and RSAmean delta was not statistically significant (B = 0.000, SE = 0.000, $t_{(38)} = -1.070$, p = 0.291). Figures 2a and 2b presents scatterplot illustrating the relationship between accumulated HSR and VHSR and the RSAmean delta. No significant regression model was observed for either CMJ or sprint performance.

Discussion

Our results revealed that variations in YYIRT performance were largely associated with accumulated session-RPE and TRIMP, underscoring the importance of internal load stimuli in enhancing aerobic capacity. Both variables individually contributed to improvements in YYIRT, as indicated by the regression analyses. Additionally, while both accumulated HSR and VHSR showed significant correlations with improvements in RSAmean, only VHSR emerged as a significant predictor of changes in this anaerobic performance measure.

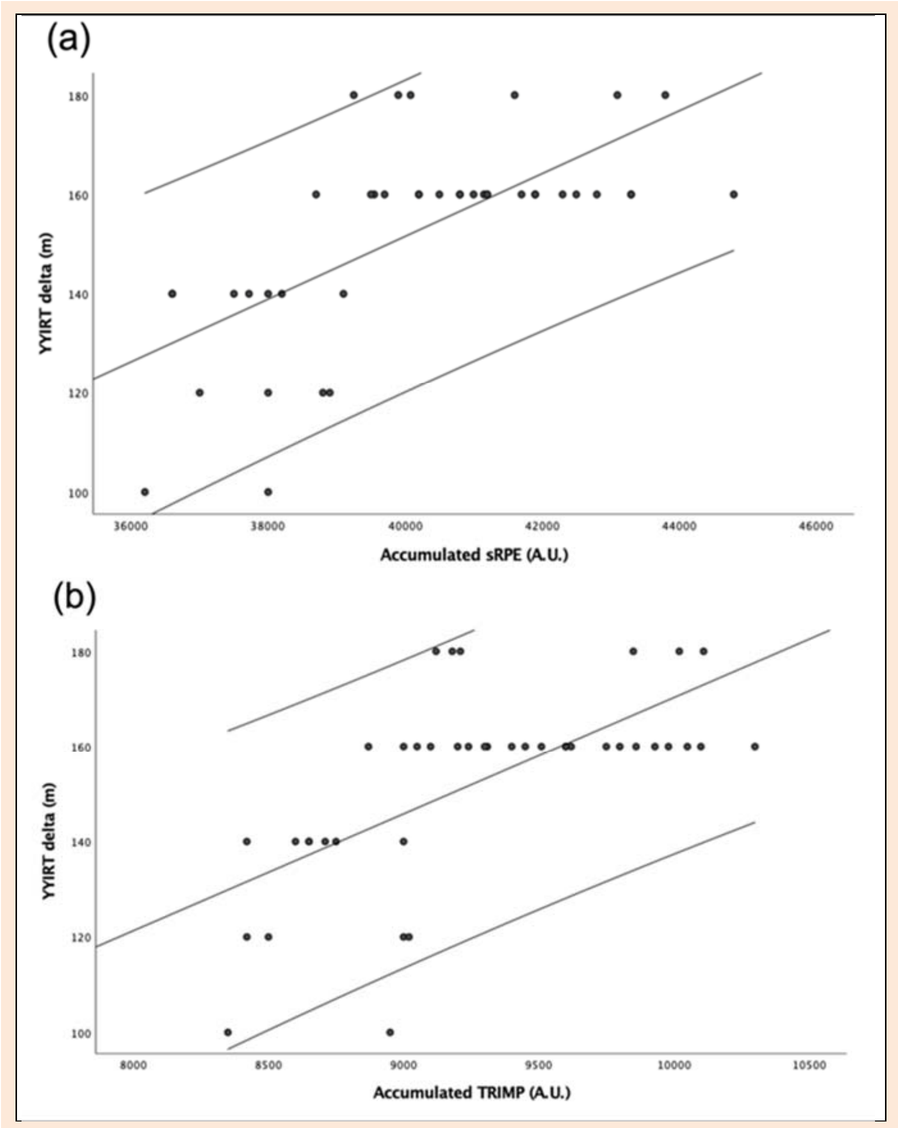

Figure 1. **Scatterplot illustrating the relationship between Yo-Yo Intermittent Recovery Test level 1 (YYIRT) delta and the (a) accumulated session rating of perceived exertion (sRPE), and (b) accumulated training impulse (TRIMP).**

Previous research has shown a significant relationship between accumulated session-RPE and improvements in aerobic capacity among soccer players. For example, a study (Clemente et al., 2020) reported a strong correlation between maximal aerobic speed and accumulated session-RPE in youth players. Similarly, another study involving under-18 male soccer players found that session-RPE was positively and strongly associated with changes in aerobic fitness (Gil-Rey et al., 2015). Our results confirm previous findings suggesting that session-RPE is a key variable to monitor, as it significantly influences the stimulus for improving aerobic fitness - an effect further supported by our regression analysis. Session-RPE reflects the integrated response of the cardiovascular, respiratory, and neuromuscular systems to training, capturing both the intensity and duration of exercise from the athlete's perspective (Haddad et al., 2017). Repeated exposure to moderate-to-high internal load over time may stimulate central adaptations, including increased stroke volume and cardiac output, as well as peripheral adaptations such as enhanced capillary density, mitochondrial biogenesis, and oxidative enzyme activity in skeletal muscle (Hellsten and Nyberg, 2016). These adaptations likely improve oxygen delivery and utilization during exercise, leading to enhanced aerobic capacity. Moreover, session-RPE is sensitive to both the external workload and internal, making it a reliable indicator of the overall training stimulus that contributes to aerobic development (Marynowicz et al., 2020).

Our study also found that accumulated TRIMP is a significant predictor of improvements in YYIRT. This supports previous studies, such as the one conducted during a soccer pre-season (Manzi et al., 2013), which reported large to very large associations between individual TRIMP and changes in VO_2max, ventilatory threshold, and Yo-Yo IR1 performance. Similarly, in elite academy soccer players (Ellis et al., 2021) it was found that individual TRIMP had the strongest relationship with changes in aerobic fitness markers. In male professional players, it was observed large to very large associations between different TRIMP methods and changes in high-intensity intermittent running capacity (Rabbani et al., 2019). Finally, another study (Papadakis et al., 2020) found moderate correlations between

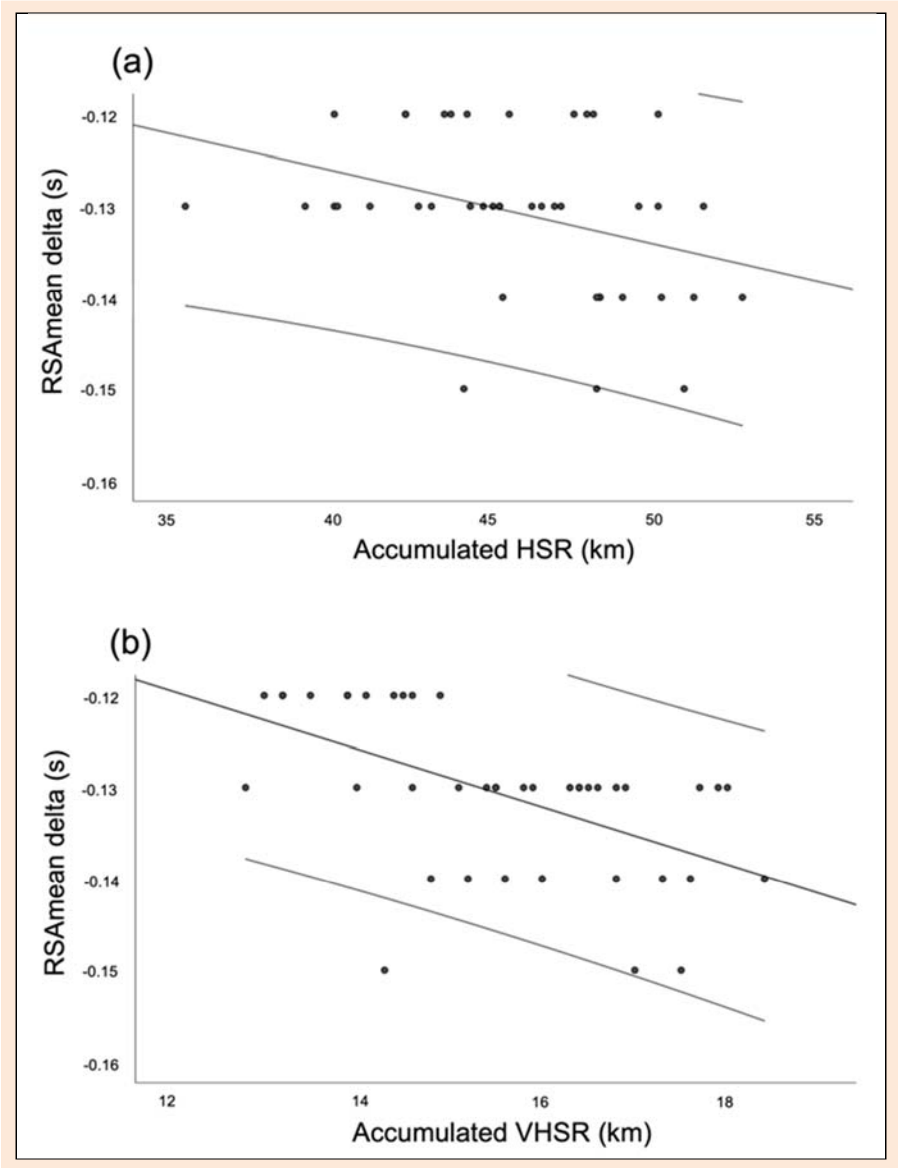

Figure 2. Scatterplot illustrating the relationship between Repeated Sprint Ability mean (RSAmean) delta and the (a) accumulated high-speed running (HSR), and (b) accumulated very high speed running (VHSR).

Banister's TRIMP and changes in maximal oxygen uptake. The associations observed between accumulated TRIMP and improvements in aerobic capacity are likely explained by the cumulative cardiovascular and metabolic demands imposed by sustained training stimuli. Edward's TRIMP captures the physiological stress experienced by the athlete, integrating both the intensity and duration of training sessions (Scott et al., 2013). Chronic exposure to such stress likely drives key central and peripheral adaptations, including increased cardiac output, blood volume, mitochondrial density, capillary recruitment, and enhanced muscle oxidative capacity (Jacobs et al., 2013) - all of which contribute to improved oxygen uptake and utilization during high-intensity efforts, such as the YYIRT.

In our study, VHSR appeared to be a potential contributor to improvements in RSAmean, among the training load parameters explored. However, the model explains about 32.2% of the variance in RSAmeandelta, which it does not prove causation. There is a gap in the existing research (Rice et al., 2022), as most studies examining the relationship between accumulated training load and fitness adaptations do not explore the impact on RSA-based variables. At VHSR intensities, the primary energy demand possibly shifts towards the anaerobic glycolytic system (Ortiz et al., 2023). This likely places a meaningful stress on the capacity of the muscles to produce ATP rapidly through the breakdown of glycogen, leading to increased glycolytic enzyme activity and improved efficiency of this pathway over time with consistent training (Roberts et al., 1982). Furthermore, the repeated bouts of high-intensity running with short recovery periods challenge the ability to buffer accumulating metabolic by-products, such as hydrogen ions, which contribute to fatigue (Girard et al., 2011). Consequently, VHSR accumulated demands eventually promote enhanced intramuscular buffering capacity, allowing for the maintenance of higher running speeds across repetitions (McGinley and Bishop, 2016). However, this remains a possibility, as we have no data to confirm this. While total distance, TRIMP, and session-RPE provide a global measure of training load, they do not specifically target the high rates of anaerobic energy turnover and metabolite accumulation that are characteristic of repeated high-speed sprints. Since HSR was not a significant predictor in the model, it may suggest a potential threshold limit that emphasizes anaerobic adaptation. However, further research is needed to fully understand the underlying mechanisms.

Our study also observed significant improvements in sprint performance and CMJ. Despite these positive outcomes, only small to moderate - and statistically non-significant - relationships were found when correlating these performance improvements with the accumulated training load parameters. This lack of strong association may be due not only to the specific training load measures selected but also to the nature of sprint and CMJ performance. Both rely on neuromuscular intensity and explosive power (Comfort et al., 2014), qualities that are often more developed through weight-room training (strength training or power training) or specific conditioning exercises rather than general training load measures. Additionally, factors such as the number of long maximal sprints performed and power accelerations may play a more critical role in driving improvements in these explosive activities (Haugen et al., 2019). Therefore, the training load parameters used in this study might not fully capture the stimuli more determinant to enhance neuromuscular performance, highlighting the need for more specific monitoring approaches in future research.

While the findings of our study provide valuable insights into the relationship between training load variables and fitness adaptations, there are several limitations that should be considered. First, our study primarily focused on accumulated session-RPE, TRIMP, total distance, HSR, and VHSR, without accounting for other potential internal and external load variables that could influence performance improvements. Future research could explore additional factors, such as heart rate variability or muscle oxygenation, to better capture the full range of physiological responses to training. Furthermore, while we identified VHSR as a significant predictor of RSA performance, the mechanisms underlying this relationship remain speculative, and further investigation is needed to explore the specific metabolic and neuromuscular adaptations associated with HSR at these intensities. Additionally, the study design limits our ability to infer causal relationships between training load and performance outcomes. Additionally, convenience sampling may limit the ability to generalize, even though different teams were considered in the analysis. Longitudinal studies tracking individual athletes over longer periods would be beneficial in determining the long-term effects of different training loads on both aerobic and anaerobic fitness. Another important limitation is the absence of control for potential confounding variables such as nutrition, sleep quality, and psychological stress, which are known to significantly influence training adaptations and performance outcomes. Moreover, the fact that this is an observational study introduces variation in the teams analyzed, particularly regarding their training processes and methodologies, which may potentially affect the relationships between variables due to differences in training approaches. Our sample also consisted solely of youth male soccer players, which may limit the generalizability of the findings to athletes in other sports or demographic groups. Future studies should consider broader populations and explore whether similar relationships between training load and fitness adaptations hold true across various sports. Finally, the limited number of participants may increase the risk of overfitting in the regression analysis. Therefore, larger sample sizes are recommended for future studies.

Despite the limitations, coaches and practitioners can use the findings from this study to optimize training load for enhancing both aerobic and RSA performance in athletes. Monitoring accumulated session-RPE and TRIMP can help track overall internal training load and guide adjustments to ensure athletes are receiving adequate stimulus to improve aerobic capacity. For RSA performance, focusing on high-speed running intensities, as indicated by VHSR, may be particularly effective in boosting repeated sprint ability. By regularly assessing these training load variables, coaches can fine-tune training sessions to avoid bad overreaching while maximizing fitness gains.

Conclusion

This study highlights the role of internal load measures, specifically accumulated session-RPE and TRIMP, in enhancing aerobic performance, as evidenced by improvements in YYIRT. Additionally, the association between VHSR and RSA performance improvements, measured by RSAmean, may indicate a possible contribution of high-intensity running to repeated sprint ability. The results suggest that while session-RPE and TRIMP are effective for monitoring aerobic adaptations, VHSR may be particularly beneficial for targeting RSA. However, the limitations of this study, such as convenience sampling, the limited number of participants, the sex analyzed, and the contextual training, should be acknowledged to exercise caution when making generalizations.

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Key points

- Internal training load measures (session-RPE, TRIMP) are strong predictors of aerobic performance improvements in youth soccer players.
- External load parameters, particularly very high-speed running (VHSR), significantly influence repeated sprint ability (RSA) adaptation, emphasizing the need for targeted load monitoring.

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