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Training load in sport: current challenges and future perspectives

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Training load in sport: current challenges and future perspectives

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Editorial: Training load in sport: current challenges and future perspectives

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KEYWORDS
training load, athletic performance, injury prevention, strength and power development, recovery strategies

Editorial on the Research Topic
Training load in sport: current challenges and future perspectives

Theoretical framework

Training load is a critical component of athletic development, serving as a fundamental determinant of performance enhancement and injury prevention (1). Factors such as training intensity, volume, frequency, and density must be carefully managed to promote positive adaptations in athletes (2). The concept of training load is not merely a measure of the amount of work performed, it is a complex interplay of factors that can significantly influence an athlete's performance trajectory (3). Understanding how to optimize training load is essential to maximizing athletic performance while minimizing the risks of excessive fatigue, injury, and overtraining, which can negatively impact an athlete's performance and ability to compete and train effectively, as well as overall health (1).

Recent research has demonstrated a clear relationship between increasing training loads and the incidence of injuries, particularly in high-impact sports where the risk of cumulative trauma is increased (4, 5). Therefore, a comprehensive understanding of training load dynamics is crucial for coaches and athletes to enable a balance to be found between performance thresholds and injury risk.

Recent advances in technology and data analytics have revolutionized the way training loads are monitored and managed. The integration of wearable devices and software applications allows real-time tracking of an athlete's physiological responses to training, providing valuable insights into their recovery needs and overall readiness to train (6). This type of data-driven approach facilitates the creation of individualized training programs that consider physical, physiological, and psychological profiles, and that consequently promote training satisfaction and reduce the risk of (7). Furthermore, the emphasis on individualized training loads is aligned with contemporary training philosophies that advocate athlete-centered training methodologies, where the athlete's contribution and experiences are essential for the optimization of the training process (8).

To clarify and further explore these issues, this Research Topic, Training Load in Sport: Current Challenges and Future Perspectives, presents a collection of studies that explored the current perspective on knowledge and challenges associated with the effects of careful manipulation and management of load to optimize performance and promote health in athletes across different sports and competitive levels.

Current challenges and future perspectives

Throughout this research topic, there were numerous contributions to investigate the current state and future perspectives in relation to training load in sport. Tilp et al. investigated the relationship between systemic and local muscle breaking points in single-leg cycling, finding strong correlations but significant individual variability. Similarly, Kårström et al. revealed discrepancies between internal and external load assessments in biathlon, suggesting that a multimodal approach is necessary for accurate monitoring. Masur et al. explored infrared thermography as a non-invasive tool to track internal burden, although inconsistencies in its relationship with traditional markers indicate that further validation is needed. Meanwhile, studies on training methods, such as those by Wei and Zheng and Quan et al., showed that small-sided games (SS) and high-intensity interval training (HITT) can generate varied benefits, especially for athletes with lower physical conditioning. Sheykhlouvand and Gharaatin in turn, analysed adaptations in cardiorespiratory fitness and biomotor skills in soccer players trained with short sprint interval training (sSIT) SSG. The sSIT promoted more homogeneous responses in ventilatory thresholds, stroke volume, and maximal power, while the SSG showed lower proportions of responders in maximal oxygen uptake, ventilatory thresholds, and anaerobic power, suggesting greater effectiveness of sSIT for consistent adaptations. Furthermore, Talsnes et al. found that splitting moderate-intensity training into two shorter sessions reduces physiological stress while maintaining training adaptations.

Physiological responses to training load go beyond performance outcomes, influencing vascular function, muscular adaptations and recovery strategies. Sugawara et al. observed that football matches induced transient reductions in arterial wave reflection without increasing arterial stiffness, suggesting adaptive responses to repeated exposure to matches. Similarly, Yu et al. recommended periodized HIIT, sprint, and threshold training for sedentary youth to maximize cardiovascular benefits while avoiding overload. Studies on strength and power development have also provided insights into how to optimize training stimuli. Cui et al. identified specific velocity loss thresholds that enhance post-activation potentiation effects in boxers. Naczk et al. demonstrated that inertial training offers small advantages over traditional resistance training for knee extensor strength. Meanwhile, Singer et al. pointed out that rest intervals longer than 60 s may provide additional hypertrophic benefits, especially beyond 90 s. Ma et al. found that blood flow restriction training may be a viable alternative to conventional strength training, offering similar improvements in muscle strength and thickness.

Injury prevention and recovery strategies are essential components of effective training load management. Huang et al. examined whole-body cryotherapy (WBC) in elite rowers, concluding that although WBC accelerates blood lactate clearance, it does not significantly improve overall recovery. Xie et al. further demonstrated that HIIT is more effective than moderate-intensity continuous training in improving post-exercise lactate clearance. In the context of injury prevention, Iwasaki et al. established a strong link between contact load and injury risk in elite rugby players, emphasizing the importance of monitoring acute and chronic workload ratios. Reverte-Pagola et al. analysed LaLiga soccer players who did not participate in the FIFA World Cup, finding that optimized load management during the tournament break led to improved sprint and acceleration performance. Furthermore, Cui et al. demonstrated that load-adjusted strength training improves punching capacity and energy efficiency in elite female boxers more effectively than traditional methods.

Finally, methodological considerations in training load research require further refinement to ensure robust conclusions. de Queiros et al. critically evaluated the systematic review by Ma et al. on BFR training, highlighting concerns related to study selection, assessment of risk of bias, and heterogeneity in comparative studies. These methodological challenges highlight the need for standardized approaches in training load research, ensuring that practitioners and researchers can develop evidence-based strategies tailored to individual athlete needs.

Studies in this Research Topic provide critical and innovative insights into training load monitoring, adaptation, and injury prevention. Advances in non-invasive monitoring tools, training periodization, and recovery strategies continue to shape evidence-based practices for optimizing athlete performance. Future research should explore individualized training load prescriptions, integrating physiological, biomechanical and technological innovations. Professionals in the field can refine training programs to achieve the best results for athletes by incorporating multifaceted monitoring strategies.

Author contributions

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EF: Writing – original draft, Writing – review & editing. RF: Writing – original draft, Writing – review & editing. JT: Writing – original draft, Writing – review & editing. RT-S: Writing – original draft, Writing – review & editing.

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Analyzing the impact of non-participation in the FIFA World Cup Qatar 2022 on LaLiga players' physical performance

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Background: Monitoring external load demands in soccer is crucial for optimizing performance and reducing injury risk. However, events like the FIFA World Cup Qatar 2022 and unexpected interruptions can disrupt load management strategies. Understanding the impact of such events on player performance is essential for effective training and recovery strategies.
Objective: This study retrospectively assessed the impact of the FIFA World Cup Qatar 2022 on the physical performance of LaLiga elite soccer players who were not part of the tournament. The aim was to analyze various external load parameters and determine the direction of their changes post-tournament.
Methods: Data from 239 LaLiga players who were not selected for the World Cup were analyzed. External load parameters from 8 matches before and after the tournament were compared. Statistical analyses, including repeated measures ANOVA, were conducted to evaluate changes in performance metrics.
Results: Minutes played and total distance covered showed no significant changes post-tournament. However, maximal speed decreased significantly ($p < 0.001$; $\eta^2_p = 0.117$). High-speed running parameters improved significantly ($p < 0.05$), except for HSRRelCount ($p = 0.074$; $\eta^2_p = 0.013$). Sprint-related variables demonstrated significant enhancements, except for SprintAbsAvgDuration, SprintMaxAvgDuration, and Sprints >85% Vel Max. Acceleration metrics showed significant improvements in Accel_HighIntensityAccAbsCount ($p = 0.024$; $\eta^2_p = 0.021$), while Accel_Accelerations showed no significant changes. Deceleration metrics remained unchanged, but Accel_HighIntensity DecAbsCount and Accel_HighIntensityDecAbsDistance increased significantly post-tournament ($p = 0.002$; $\eta^2_p = 0.040$, $p = 0.001$; $\eta^2_p = 0.044$, respectively).
Conclusion: Non-participant LaLiga players demonstrated enhanced performance in most external load metrics after the FIFA World Cup Qatar 2022. These findings highlight the importance of effective load management during periods of competition interruption and suggest strategies to optimize performance and reduce injury risk. Further research should consider holistic performance metrics and internal load parameters to provide comprehensive insights into player response to mid-season tournaments.

KEYWORDS
soccer, football, match analysis, time-motion analysis, GPS device

Introduction

Monitoring external load demands of the game is a challenge for team sports such as soccer (1, 2). Weekly changes in external load are necessary to optimize the microcycle in order to obtain the maximum performance during games and to reduce injury risk (3). Nonetheless, the monitorization of the external loads and thus the demands of the game constitutes the central element from which the microcycle is organized (4, 5). In this context, it is important to note that the physical performance of the soccer players Typically experience seasonal fluctuations that should be monitorized to orient training loads and thus regulating the training stimulus (6). Therefore, soccer players performance during games are strongly influenced by the moment of the season. Consequently, several studies have examined the parameters of external load across a typical season (7, 8). Several forms of assessing external load have emerged during recent years such as the use of global navigation satellite systems (GNSS) (9), local positioning systems for indoor competitions (10) or tracking systems through high-definition cameras (11). All these methods have shown to be reliable and valid for assessing external load demands of the game (12), which is an essential task for designing microcycles and training sessions (13, 14). Nonetheless, certain events, such as the interruption of the competition due to COVID-19 (15), the recent introduction of a mid-season World Cup (16, 17), or breaks for international competitions without season-to-season patterns (18), can disrupt the distribution of loads during the season. However, professional soccer teams need information about the impact of these emerging events to better understand the implications in physical performance, especially in the main external load parameters such as total distance covered, accelerations, decelerations, high-speed running or sprinting, and thus manage the load patterns. FIFA World Cup Qatar 2022 constituted a challenging event for soccer teams, since the regular competition was interrupted for a month (17, 19). This tournament created a scenario unprecedented until now, where some players competed at the highest competitive level for a month, while others would not receive a competitive stimulus for over 4 weeks. While it is known that similar precedent scenarios such as COVID-19 lockdown resulted in a decrease in match external load outcomes performance (15), it is unknown how shorter breaks such as FIFA World Cup Qatar 2022 affected to the Spanish professional teams. If training loads are not well managed, this period could partially detrain World Cup non-participants. Short detraining periods of 2–4 weeks have demonstrated to not affect maximal neuromuscular responses in soccer players (20, 21). However, they could have a negative impact on repeated sprint ability (RSA) (22, 23) or body composition (24). Nonetheless, to the best of our knowledge, no previous studies have analyzed the impact of mid-season tournaments such as the FIFA World Cup Qatar 2022 on non-participants that reduce the competition but not the training stimulus. Some authors (17) advanced that this tournament would affect to the physical performance of the players, but without clear statements about the directions of the changes suffered due to the World Cup.

Assessing the impact of mid-season events such as FIFA World Cup Qatar 2022 could help strength and conditioning coaches to optimize the training process during periods of lack of competition. Specifically, knowing the variables that are most affected after a period of competitive inactivity can help create training tasks that promote the execution of those actions with greater impact, thus improving external load management. Consequently, the aim of the present study was to retrospectively assess the impact of the FIFA World Cup Qatar 2022 on physical performance of LaLiga elite soccer players. The main hypothesis was that the period of inactivity has affected the external load metrics performance. Nonetheless, this study could determine in which direction (i.e., improvement or deterioration) the variables were affected.

Materials and methods

Study design

The study employed a retrospective design to evaluate how the performance of LaLiga players who were not called up by their national teams was influenced by the FIFA World Cup Qatar 2022. It compared the external load parameters observed in the 8 matches leading up to the World Cup with those recorded in the 8 subsequent matches during the regular league season.

Sample

Data were collected from professional soccer players from LaLiga who were not selected to represent their national teams in the FIFA World Cup Qatar 2022. Specifically, data were retrospectively collected from the 8 matches played by each player before the World Cup and 8 matches following the resumption of domestic league competition. For inclusion in the analysis, players were required to have accumulated a minimum of 90 min of playtime across the 8 pre-World Cup matches and 90 min across the 8 post-World Cup matches. Moreover, no injured players during data collection period were included in analyses. In total, 239 players met these criteria and were included in the analyses. There were included 98 defenders, 100 midfielders and 41 forwards with 27.39 ± 4.18 years old.

Variables

In the assessment of external load parameters, the study gathered the following variables for each player in every match: minutes of game played, total distance covered in meters, maximal speed attained, high-speed running (HSR) outcomes, sprint outcomes, acceleration outcomes, and deceleration outcomes, which have been established as key performance indicators and key external load metrics to define the player profile (25–27).

HSR variables scrutinized encompassed the total count of high-speed running actions (>21 km/h) (HSRAbsCount), the total distance covered during high-speed running (HSRAbsDistance), the total duration of high-speed running (HSRAbsDuration), the number of actions performed at speeds exceeding 75.5% of the player's historical maximum speed based on the WIMU (i.e., GPS) Profile (HSRRelCount).

Sprint variables examined included total time spent sprinting over 24 km/h (SprintDur), total count of sprinting actions over 24 km/h (SprintAbs), average duration of sprinting actions (SprintAbsAvgDuration), total duration of all sprinting actions (SprintAbsDuration), count of the number of times a player has repeated an absolute sprint during a predefined RSA period of 60 s (SprintAbsRepetitions), count of sprints exceeding 85% of the player's maximal velocity based on the WIMU profile (Sprints >85% Vel Max), overall distance covered during sprints (PlayerDistanceSprint), and total count of sprints performed (PhysicalNumberofSprints).

Acceleration outcomes comprised the count of all accelerations over 3 m/s^2 (Accel_Accelerations), and total count of high-intensity accelerations (Accel_HighIntensityAccAbsCount). Lastly, deceleration outcomes entailed the count of all decelerations (Accel_Decelerations), total count of high-intensity decelerations under −3 m/s^2 (Accel_HighIntensityDecAbsCount), and total distance covered during high-intensity decelerations under −3 m/s^2 (Accel_HighIntensityDecAbsDistance).

Instruments

Following previous data collection described methodology (28), running performance during matches was evaluated using an advanced multicamera computerized optical tracking system called TRACAB (ChryronHego VID, New York, NY). This system was managed through the Mediacoach application (LaLiga, Madrid, Spain), operating at a sampling frequency of 25 Hz (i.e., 25 samples per s). Previous studies assessing the reliability and accuracy of this system for the designated variables demonstrated strong correlations ($r > .80$) and high intraclass correlation coefficients ($r > .75$) between the Mediacoach multicamera tracking system and the Global Positioning System. Additionally, minimal standard errors of estimate (≤.60) were observed across all speed categories analyzed in this investigation (11, 29, 30).

Statistical analysis

Three distinct analyses were performed to assess how the FIFA World Cup Qatar 2022 affected player performance, with each analysis focusing on specific variables. Initially, alterations in players' minutes of game played were explored by summing the minutes from the 8 matches before and after the World Cup. A repeated measures analysis of variance (ANOVA) was then applied to compare the differences in playing time pre and post-tournament. Secondly, the Maximal Speed variable was assessed by identifying the highest speed attained by players in matches lasting over 60 min before and after the World Cup. Subsequently, a repeated measures ANOVA was used to assess variations in maximal speed pre and post-tournament. Finally, mean values for the remaining performance variables (total distance covered, HSR, sprints, accelerations, and decelerations) were calculated for matches played before and after the World Cup, considering only those where players participated for over 60 min. Repeated measures ANOVA tests were conducted to compare the means of each variable before and after the World Cup, offering insight into the effects of the nearly month-long interruption without competitions on performance aspects of players who were not selected for the World Cup. All statistical analyses were performed using Jamovi Statistical Software (The jamovi project (2022). jamovi. (Version 2.3) [Computer Software]. Retrieved from https://www.jamovi.org) and Microsoft Excel. The significance level for the statistical tests was set at $p < 0.05$ with a 95% confidence interval (CI). Effect sizes were also calculated using partial eta squared (η^2_p) to assess the magnitude of change in the variables, with values of 0.01 considered small, 0.06 medium, and over 0.14 large.

Results

Impact of FIFA World Cup Qatar 2022 on minutes of game

The repeated measures ANOVA test indicated a non-significant effect on minutes of game played ($p = 0.468$; $\eta^2_p = 0.002$) when comparing pre-World Cup vs. post-tournament periods. Similarly, there was a non-significant difference in the number of matches with >60 min played before and after the World Cup ($p = 0.109$; $\eta^2_p = 0.011$). Figure 1 provides a summary of the alterations in minutes played.

Impact of FIFA World Cup Qatar 2022 on total distance

The repeated measures ANOVA test revealed non-significant differences between pre- World Cup vs. 8 subsequent matches in PlayerPhysicalDistance ($p = 0.407$; $\eta^2_p = 0.003$). Figure 2 shows changes in total distance covered.

Impact of FIFA World Cup Qatar 2022 on maximal speed

The repeated measures ANOVA test indicated a significant influence of the World Cup on PlayerPhysicalMaximumSpeed ($p < 0.001$; $\eta^2_p = 0.117$), suggesting the superiority of pre-tournament outcomes. Maximal speed changes are shown on Figure 3.

Impact of FIFA World Cup Qatar 2022 on high-speed running outcomes

The repeated measures ANOVA test demonstrated significant differences when comparing 8 previous FIFA World Cup Qatar

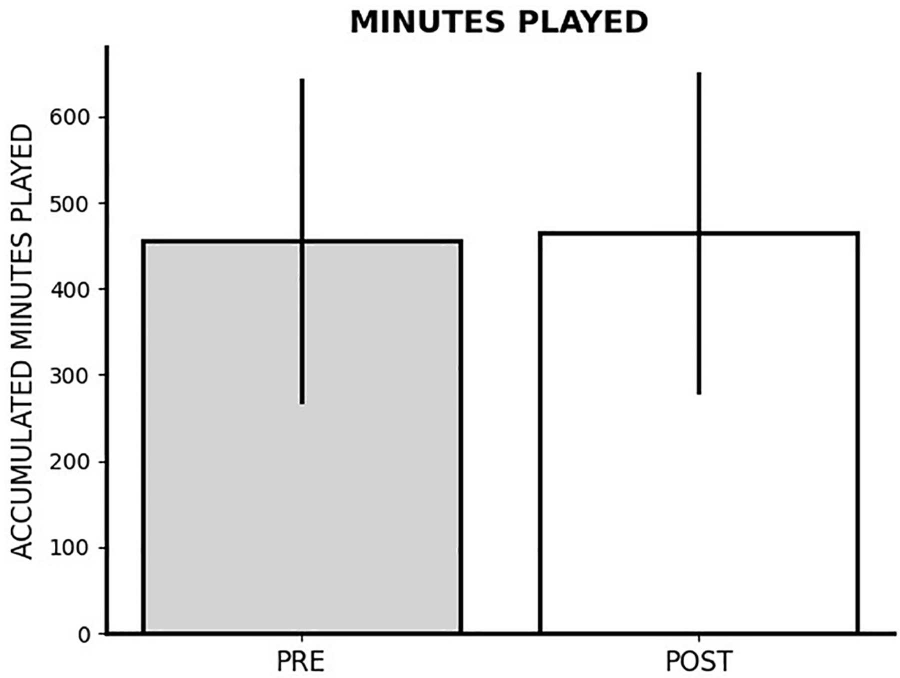

FIGURE 1
Changes in accumulated minutes played after FIFA World Cup Qatar 2022.

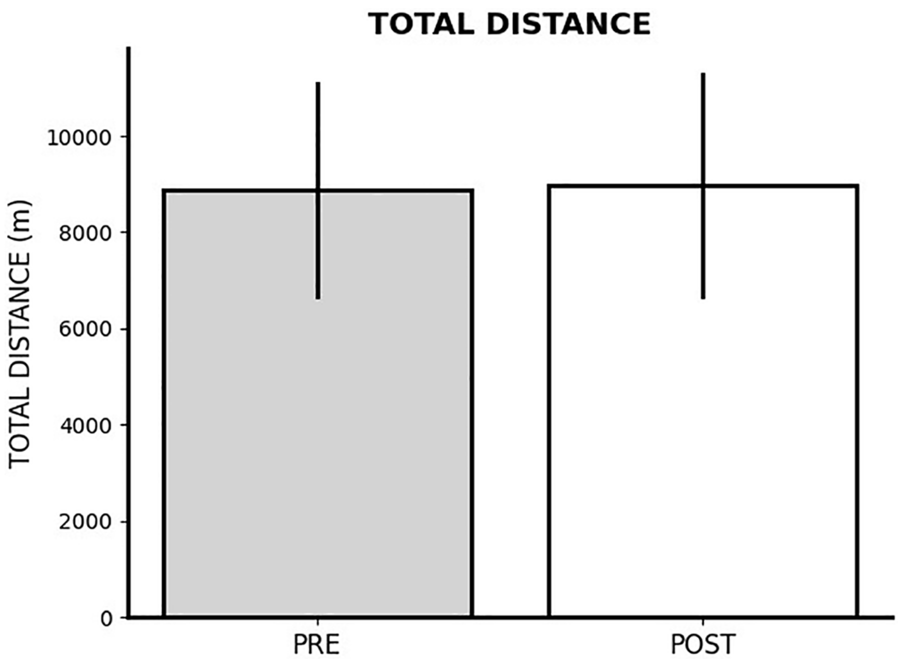

FIGURE 2
Changes in total distance covered after FIFA World Cup Qatar 2022.

2022 matches vs. 8 subsequent matches on various high-speed running parameters. Specifically, HSRAbsCount ($p < 0.001$; $\eta^2_p = 0.048$), HSRAbsDistance ($p = 0.001$; $\eta^2_p = 0.043$), and HSRAbsDuration ($p < 0.001$; $\eta^2_p = 0.051$) all showed the superiority of post-tournament outcomes. However, HSRRelCount ($p = 0.074$; $\eta^2_p = 0.013$) exhibited non-significant effects of time measures.

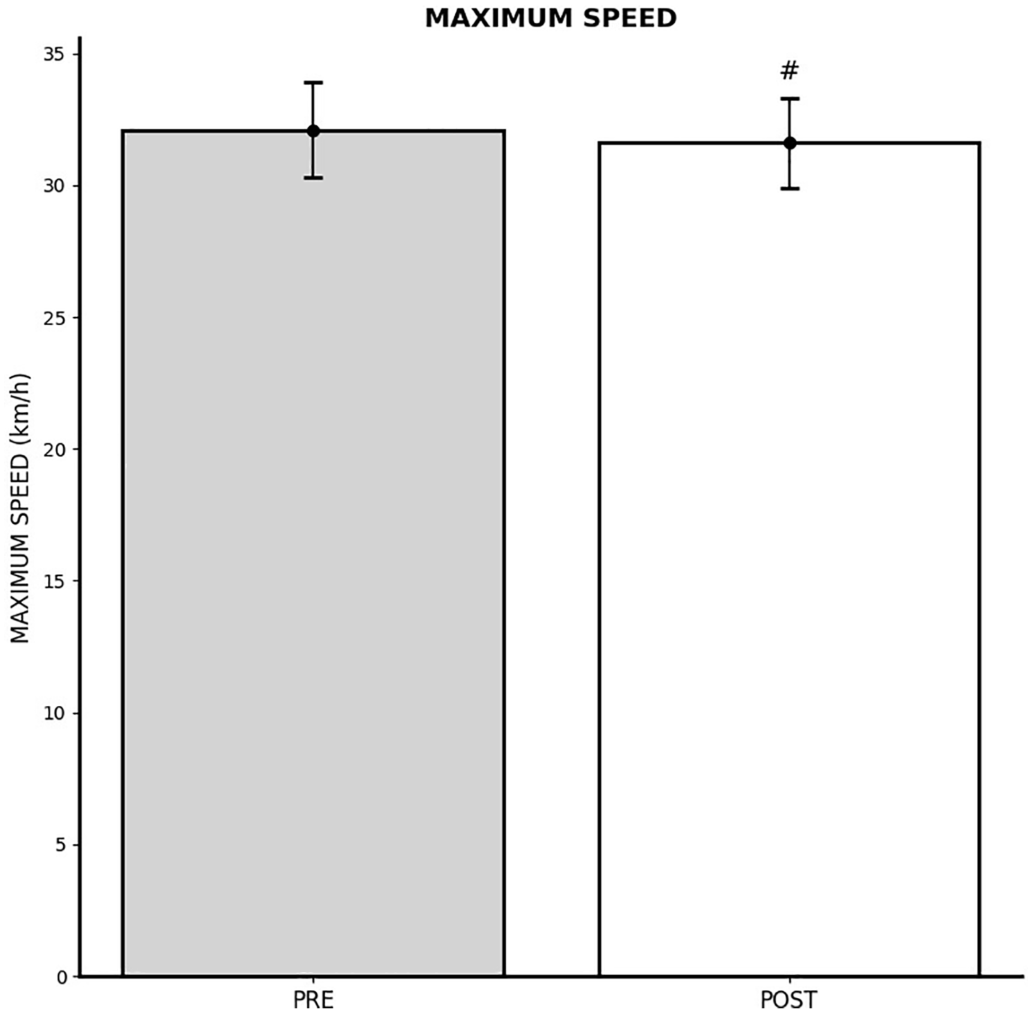

FIGURE 3
Changes in maximum speed reached after FIFA World Cup Qatar 2022. #Significantly lower than PRE.

High-speed running outcomes differences pre-post World Cup are shown on Figure 4.

Impact of FIFA World Cup Qatar 2022 on sprint outcomes

The repeated measures ANOVA test revealed significant differences between time points across various sprint-related variables. Specifically, PlayerDistanceSprint ($p = 0.001$; $\eta^2_p = 0.042$), PhysicalNumberofSprints ($p = 0.001$; $\eta^2_p = 0.042$), SprintDur ($p = 0.010$; $\eta^2_p = 0.028$), SprintAbs ($p = 0.004$; $\eta^2_p = 0.034$), SprintAbsDuration ($p = 0.003$; $\eta^2_p = 0.038$), SprintAbsRepetitions ($p = 0.015$; $\eta^2_p = 0.026$) all favored post-World Cup outcomes. However, SprintAbsAvgDuration ($p = 0.306$; $\eta^2_p = 0.004$), SprintMaxAvgDuration ($p = 0.780$; $\eta^2_p < 0.001$) and Sprints >85% Vel Max ($p = 0.658$; $\eta^2_p = 0.001$) exhibited non-significant effects of time measures. An overview of the changes in sprinting parameters is shown in Figure 5.

Impact of FIFA World Cup Qatar 2022 on accelerations outcomes

The repeated measures ANOVA test indicated significant effects of the World Cup on Accel_HighIntensityAcc AbsCount ($p = 0.024$; $\eta^2_p = 0.021$), demonstrating significant improvements in post-World Cup measures. However, Accel_Accelerations ($p = 0.193$; $\eta^2_p = 0.007$) exhibited non-significant effects of time measures. Acceleration changes are shown on Figure 6.

Impact of FIFA World Cup Qatar 2022 on deceleration outcomes

The repeated measures ANOVA test revealed no significant differences between pre-World Cup vs. post-World Cup periods in Accel_Decelerations ($p = 0.191$; $\eta^2_p = 0.007$), but significant

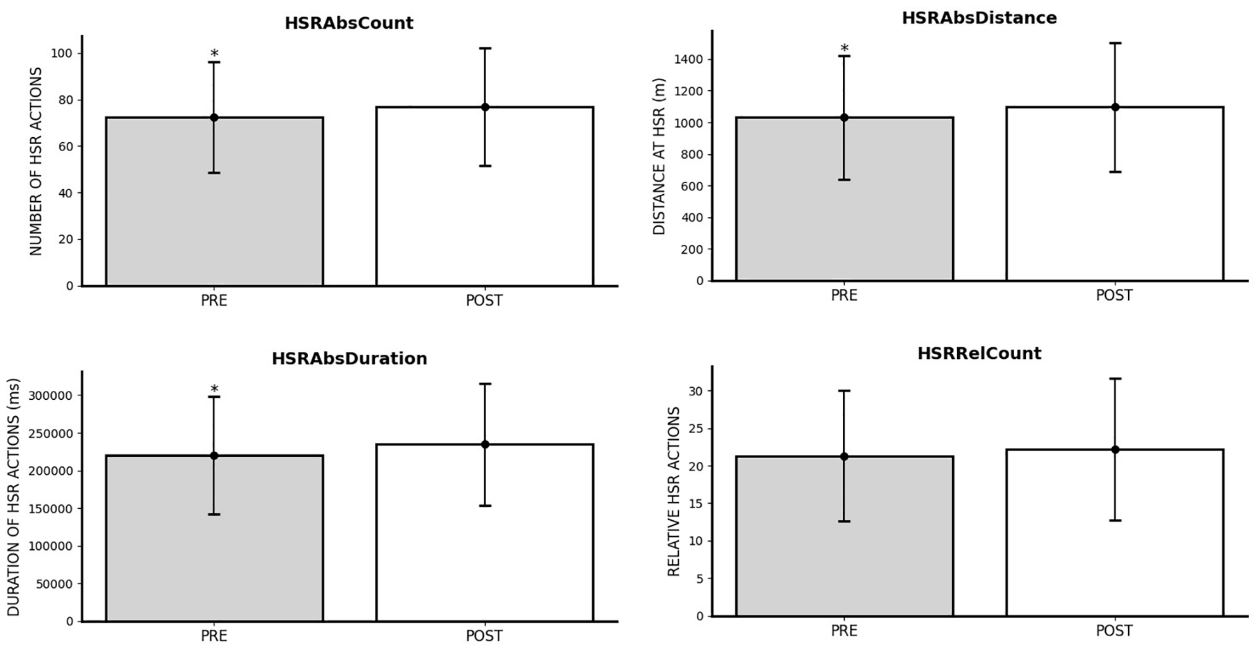

FIGURE 4
Changes in high-speed running outcomes after FIFA World Cup Qatar 2022. *Significantly lower than POST.

increases after World Cup on Accel_HighIntensityDecAbsCount ($p = 0.002$; $\eta^2_p = 0.040$), and Accel_HighIntensityDecAbsDistance ($p = 0.001$; $\eta^2_p = 0.044$), indicating significant enhancements in post-World Cup measures. Pre-post World Cup differences are displayed on Figure 7.

Discussion

The present study aimed to assess the impact of FIFA World Cup Qatar 2022 on non-participants physical performance in LaLiga players analyzing 8 matches pre- and post-tournament.

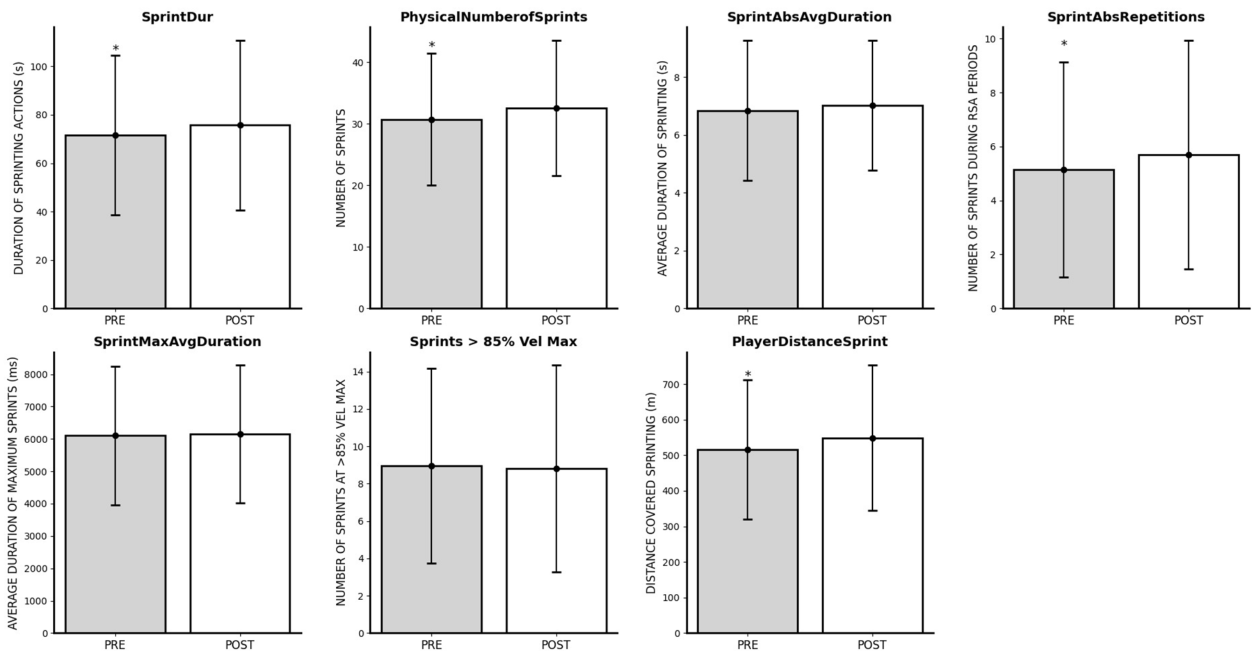

FIGURE 5
Changes in sprinting outcomes after FIFA World Cup Qatar 2022. *Significantly lower than POST.

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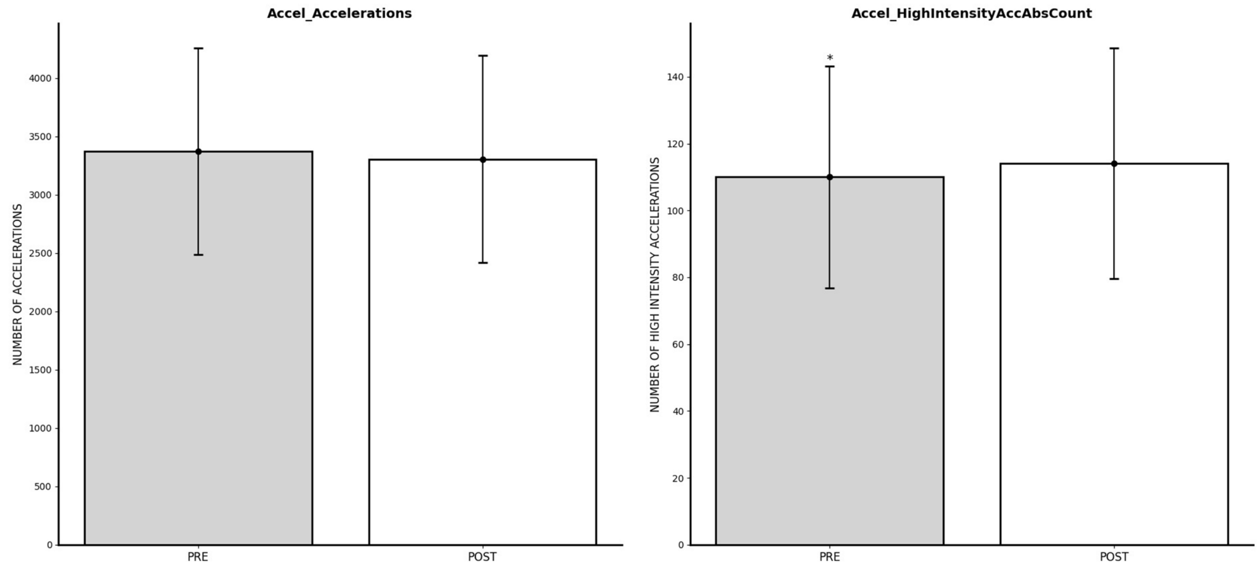

FIGURE 6
Changes in acceleration outcomes after FIFA World Cup Qatar 2022. *Significantly lower than POST.

Before this study, there were no information about the impact of the World Cup on regular season performance variables and our results could help coaches to better manage future similar events. According to our initial hypothesis, this study showed substantial changes in match performance in most of the analyzed variables, revealing significant increases in most of the analyzed variables, except for maximal speed. Nonetheless, maximum speed performance showed a significant reduction after FIFA World Cup Qatar 2022. These findings could help coaches to emphasize the training of this variable. It could be of special relevance the achievement of similar or even greater maximum speed of sprinting, since sprinting is the most frequent action prior scoring a goal (31). In addition, a review has highlighted the importance of this action in the game given the development of the game and due to the increasing peak velocities observed in soccer players (32). Therefore, disposing a higher sprinting speed could determine the difference between scoring or not a goal. This reduction in maximal speed could be attributed to the lower

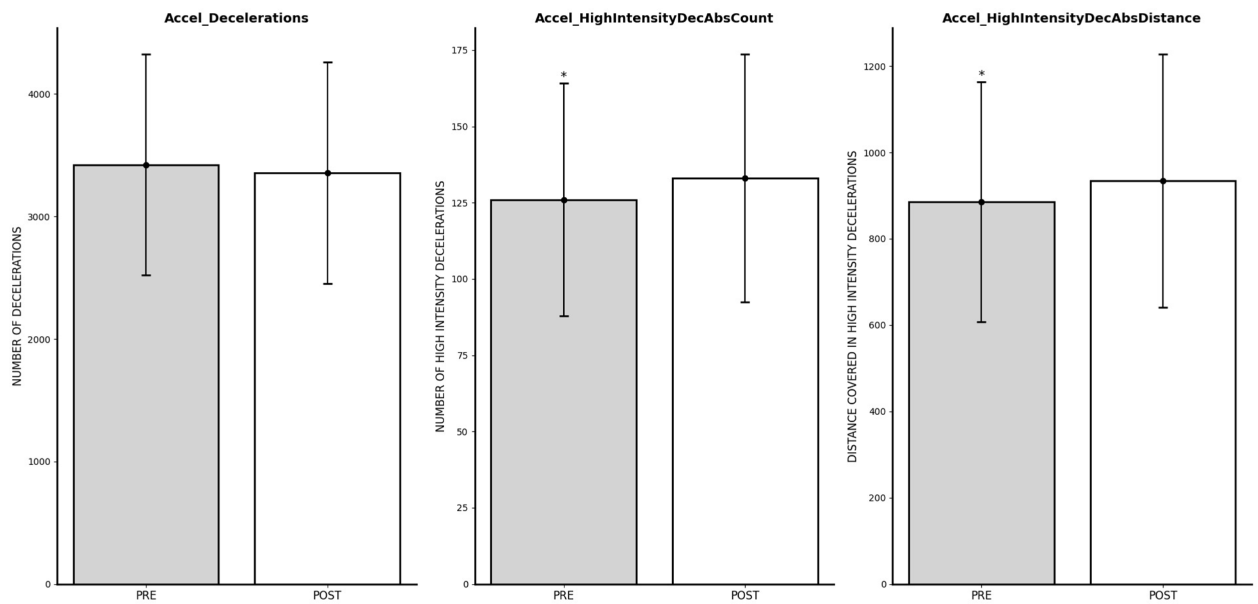

FIGURE 7
Changes in deceleration outcomes after FIFA World Cup Qatar 2022. *Significantly lower than POST.

number of maximal sprinting scenarios during training when compared to official matches. In this line, the cessation of competition could have resulted in a reduction of the performance in maximal speed. Therefore, during periods of inactivity of competition maximal sprinting speed tasks should be carried out to not decrease performance when returning to competition. In addition, this reduction could be also explained by the decrease in the number of minutes played when comparing pre-post World Cup and thus in the exposure of competitive stimulus. In addition, our analyses showed a medium effect size for the changes produced in maximal speed, reinforcing the need for focusing on this training variable during short breaks of competition. The number of high intensity accelerations using absolute thresholds showed a significant increase when comparing pre-post World Cup values. Nonetheless, it is important to highlight the importance of contextualizing the thresholds as showed in previous studies (33, 34), but it is also important to note that no consensus exists about the implementation of specific and relative thresholds (34), so future studies should reach consensus about the implementation of relative thresholds to further analyzing changes in high-intensity accelerations after mid-season tournaments such as the analyzed in the present study and to report these values in a better way. Anyway, the number of high intensity accelerations has shown to be the greatest during matches in the microcycle pattern (i.e., match demands in number of accelerations are greater than in training sessions) (35, 36). Nevertheless, previous research has shown that number of accelerations decrease throughout the season (36), but the results of the present study have shown an increase in this parameter, so substantial breaks in competition could result in an increase in high-intensity accelerations and most of the external load variables based on the results of the present study. Moreover, the correlation between accelerations performed during training sessions and accelerations during matches is very low (37), so performing more accelerations during training not necessarily result in greater performance during matches, reinforcing that it is the break in the competition that has generated an increase in this metric and not a greater number of accelerations in training. However, future studies should analyze the load patterns in training sessions to conclude if the possible modification of the training periodization could have influenced these changes in match outcomes.

The main finding of the present study is that external load parameters were greater after the FIFA World Cup Qatar 2022. Results of the present study showed greater performance in variables related to high-speed running over 21 km/h, greater performance in most of the sprinting variables and greater performance in deceleration variables. The results of the present work are in line with findings that neuromuscular performance after short-term detraining could be enhanced (20, 21), Nonetheless, the detraining period in this study should be understood as a break of competitive matches, since on-field training continued in this period. To the best of our knowledge, this is the first study in assessing the differences in external load parameters after a cessation of the competition but not in training. Future studies should address the pattern of loads performed during these periods without competition to better understand the mechanism in the improvement of the external loads parameters as shown in this study. However, these findings could help coaches to better manage recovery strategies, as well as load management. In addition, it would be interesting to analyze the impact of FIFA World Cup Qatar 2022 on those players who participated in the tournament. Greater exposures to high-speed running and sprinting have demonstrated to produce high fatigue levels in the posterior chain and especially in the hamstrings (38–40), which could increase the risk of injury in this muscle group (39, 41). In this line, it could be essential to optimize the recovery strategies to minimize loading on the hamstrings and improve sport performance (42, 43). However, increasing fitness levels, as well as neuromuscular strength levels is the best strategy to enhance recovery, since players with greater fitness and strength levels have demonstrated to recover faster (44). Therefore, strength and conditioning coaches should take advantage of these periods without competition to increase fitness levels and strength performance. In addition, these results could serve to enhance team management, since based on the results of this study, coaches can anticipate better physical performance from players who have not participated in the mid-season tournament. In addition, our study provides valuable insights into how coaches can adjust training regimens to optimize player performance, particularly in areas such as sprinting speed and high-intensity accelerations, which are crucial for on-field success.

Several limitations should be highlighted from the present study. Firstly, only physical performance has been evaluated and the results of the present study should be complemented with technical-tactical metrics, because better physical performance does not necessarily translate to better sport performance (45, 46). A more holistic approach integrating technical-tactical factors could help optimize the training process by better understanding the effects of mid-season tournaments such as FIFA World Cup Qatar 2022 on different dimensions of the game. Consequently, the analysis of technical-tactical metrics could have impacted on an integrated practical application on how the training of sprinting speed is performed during soccer tasks that favor the worsened patterns observed in this study. Another limitation that should be highlighted is the lack of analysis of internal load parameters, that could add valuable information to understand how the increase in external load parameters demonstrated in this study affect to the response of the players. Integrating internal load parameters is necessary to improve the periodization of the microcycles, thus contributing to improve the implications of this study on performance and the reduction of non-contact injury risk (47) by managing properly the player load. Previous studies have shown a clear relationship between external and internal load parameters and injury risk (48), so this study could contribute to a better management of load patterns to reduce the injury risk. Therefore, a better integration of external and internal parameters could have provided more clear directions on how to manage not only the metrics of the players during tasks, but also their internal responses. Another limitation that could be considered is the number of matches selected for analysis, since there is no consensus about the number of observations pre- and post-event to analyze. In this line, our aim was to collect a wide range of matches to have firm results of the influence of the World Cup on physical performance, but consensus is needed in the number of matches selected for analysis. Lastly, only Spanish LaLiga players were analyzed. In this line, the influence of the country of competition (i.e., Spain) makes difficult to extrapolate the results of this study to another leagues, since substantial differences in external load and game patterns exist between top European leagues (49). Therefore, future studies should analyze how these mid-season tournaments affect to the players of different countries in order to study if the responses of external load metrics are dependent on the country and the style of playing.

Conclusion

The present study provides valuable insights into the impact of the FIFA World Cup Qatar 2022 on the physical performance of Spanish LaLiga players who did not participate in the tournament. Our findings indicate significant improvements in various external load parameters following the World Cup, suggesting potential implications for load management and performance optimization strategies. Specifically, non-participants demonstrated enhancements in the number of high-speed running actions, distance covered at high-speed running, duration of high-speed running actions, duration of sprinting actions, number of sprints performed, number of sprints performed during repeated sprint ability periods, distance covered during sprinting, number of high-intensity accelerations, number of high-intensity decelerations, and the distance covered during high-intensity decelerations. However, it's worth noting that maximum speed performance experienced a reduction post-tournament.

These findings underscore the importance of effectively managing short periods without competition to maximize on-field performance and minimize injury risk. Coaches and sports scientists can use this information to tailor training regimens and recovery strategies during breaks in the competition calendar, thereby optimizing player readiness and overall team performance. These results have significant implications for athlete preparation and injury prevention strategies in professional soccer.

Data availability statement

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical approval was not required for the studies involving humans because LaLiga approved this study, since data was obtained by this institution. This study was conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements because the study did not require participants approval.

Author contributions

GR: Data curation, Formal Analysis, Methodology, Resources, Writing – original draft, Writing – review & editing. JP: Formal Analysis, Investigation, Methodology, Resources, Software, Writing – original draft, Writing – review & editing. Jd: Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. RL: Conceptualization, Data curation, Funding acquisition, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing. RR: Conceptualization, Data curation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. AF: Conceptualization, Data curation, Investigation, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Optimal homeostatic stress to maximize the homogeneity of adaptations to interval interventions in soccer players

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This study examined the uniformity of adaptations in cardiorespiratory fitness and bio-motor abilities by analyzing individual responses to measures representing the mentioned qualities. Twenty-four male well-trained soccer players (Age = 26 ± 4 years; stature = 181 ± 3.8; Weight = 84 ± 6.1) were randomized to two groups performing short sprint interval training [sSIT (3 sets of 10 × 4 s *all-out* sprints with 20 s of recovery between efforts and 3 min of rest intervals between sets)] or a time-matched small-sided game [SSG (3 sets of 3 v 3 efforts in a 20 × 15 m area with 3 min of relief in-between)]. Before and after the 6-week training period, aerobic fitness indices, cardiac hemodynamics, and anaerobic power were assessed through a graded exercise test utilizing a gas collection system, noninvasive impedance cardiography, and a lower-body Wingate test, respectively. Also, sport-specific bio-motor abilities were determined by measuring linear speed, change of direction, and jumping ability. Comparing inter-individual variability in the adaptive changes by analyzing residuals in individual adaptations indicated that sSIT induces more uniform changes in the first and second ventilatory threshold (VT_1 & VT_2), stroke volume, and peak power output across team members than SSG. SSG also yielded lower proportions of responders in $\dot{V}O_{2\,max}$, VT_1, VT_2, peak, and average power output compared to sSIT. Additionally, the coefficient of variation in mean group changes in measures of aerobic fitness and bio-motor abilities in response to sSIT were lower than in SSG. Short sprint interval training induces more homogenized adaptations in measures of cardiorespiratory fitness and anaerobic power than small-sided games across team members.

KEYWORDS

cardiorespiratory fitness, bio-motor abilities, athletic performance, team sport, anaerobic power

1 Introduction

Typically, responses to different exercise interventions are presented as average group values, with the presumption that these values represent individual responses. However, individual adaptations to a standardized intervention vary among athletes with different physiological profiles and locomotor abilities (Mann et al., 2014). Moreover, the quantity of workload imposed by some sport-specific interventions could be unequal due to the inability of intervention to control several influencing factors in workload (Hill-Haas et al., 2008a, 2008b). Such non-uniform physical stresses may result in heterogeneous adaptations among athletes of a group or members of team sports (Clemente et al., 2020; Sandford et al., 2021).

Soccer is a famous team sport characterized by intermittent explosive movements (i.e., acceleration and deceleration, repetitive short-distance sprinting, jumping, and turning in different directions) fueled by the anaerobic metabolic pathway (Rampinini et al., 2011; Nyberg et al., 2016; Mohr et al., 2023). Also, heightened aerobic capacity prevails during less intense activities to accelerate recovery and contribute to sustaining efforts throughout matches. Hence, it is essential to focus on improving both anaerobic and aerobic metabolic pathways to enhance soccer players' performance during a game (Nyberg et al., 2016; Arazi et al., 2017). Various methods have been developed to improve these attributes. High-intensity interval training (HIIT), in its various forms, has proven to be an effective intervention for boosting both cardiorespiratory fitness and anaerobic power in soccer athletes (Dai and Xie, 2023). Similar to the nature of HIIT, soccer involves repetitive, intense actions interspersed with rest intervals of low to moderate intensity (Laursen and Buchheit, 2019). Hence, HIIT could be considered a sport-specific approach to enhance the metabolic conditioning of soccer players.

Several HIIT prescribing methods have been proposed for soccer players, aiming to ensure athletes achieve the necessary exercise intensity during their training sessions in a controlled and sport-specific manner (Laursen and Buchheit, 2019). According to the important principle of training specificity and considering the technical and tactical demands associated with team sports, HIIT in the form of Small-Sided Games [SSGs (i.e., so-called game-based conditioning)] have received exponential growth in interest (Clemente et al., 2021) since the publication of the first systematic review on the topic (Hill-Haas et al., 2011). This is because SSGs simulate the dynamics of an official game while allowing for specific adjustments to emphasize particular behaviors and actions (Clemente, 2020). Given the potency of enhancing physical performance, technical skills, and tactical awareness concurrently, SSGs are considered a time-efficient training approach (Arcos et al., 2015). Nevertheless, despite the mentioned training effectiveness, SSGs have their limitations. Variances in the quantity of strenuous activities performed during SSGs result in inter-individual differences in workload. This results in heterogeneous adaptations to the training among team members (Hill-Haas et al., 2008a; 2008b, and 2011). These constraints support utilizing a less specific yet more controlled HIIT format, such as running-based repeated sprints (Laursen and Buchheit, 2019). As these interventions are performed at maximum effort, they can be prescribed without assessing an individual's physiological limits (e.g., maximum oxygen uptake [$\dot{V}O_{2\,max}$]) to adjust the exercise intensity (Laursen and Buchheit, 2019). However, due to the considerable psychological demands and the extreme physical exertion, it is speculated that athletes with different levels of physical fitness represent varied tolerance to traditional sprint interval training, which is performed as 30–45 s *all-out* sprints. This variability can induce diverse mechanical stress, unidentical physiological demands, and non-uniform adaptations among team members (Sandford et al., 2021).

Recent research has suggested that utilizing shorter-duration sprints, known as short sprint interval training (sSIT) with efforts lasting between 3 and 10 s, could be considered an alternative to the traditional repeated sprint training. This approach has the potential to generate similar adaptive responses while simultaneously improving enjoyment and reducing the perceived exertion rate (Flores et al., 2018; McKie et al., 2018). Implementing sSIT has been proven to generate elevated mechanical responses and decreased peripheral fatigue. This outcome is attributed to the dependence on the ATP-PCr pathway and a reduction in glycolytic activity (Boullosa et al., 2022). Given that the majority of sprints in a soccer match are shorter than 10 m and involve a combination of explosive (rapid acceleration) and leading (gradual acceleration) movements (Dupont and McCall, 2016), sSIT might be considered a sport-specific intervention for soccer players. Nevertheless, limited studies regarding the effects of sSIT on sport-specific performance measures restrict capturing a complete picture of its potency in improving cardiorespiratory fitness and bio-motor abilities in soccer players. For coaches to effectively design programs to improve players' proficiency in soccer games, they must thoroughly understand the varied responses to different types of HIIT interventions. Accordingly, this study aimed to compare the magnitude of the adaptations to SSGs and sSIT and inter-individual variability in adaptive responses in well-trained soccer players. Given that the workload of sSIT is more controllable than SSGs, we hypothesized that sSIT would result in more homogenized adaptations among team members than SSG.

2 Materials and methods

2.1 Study design

Figure 1 represents an overview of the experimental protocol. The research utilized a randomized controlled trial featuring two experimental groups. Before the commencement of the study, participants underwent a set of assessments, including both lab- and field-based measurements, to assess cardiorespiratory fitness indicators and soccer-specific bio-motor abilities. Participants underwent a graded exercise test on the initial visit to assess maximum oxygen uptake ($\dot{V}O_{2\,max}$) and associated physiological variables. Subsequently, the second visit involved the measurement of Wingate-based anaerobic power. Jumping ability was measured on the third testing session, and change of direction (COD) and linear speed were evaluated on the fourth occasion. Testing sessions were separated by a 24-h recovery period, during which participants were instructed to abstain from consuming caffeine and alcohol, as well as to avoid engaging in strenuous exercise (Gharaat et al., 2020; Barzegar et al., 2021). Approximately 48 h following the last testing session, participants commenced the 6-week training program, and 48 h after the final training session, they underwent the identical testing procedure, following the same order and under the same conditions as the pre-test. Measurements were carried out by two expert technicians who were blinded to the interventions.

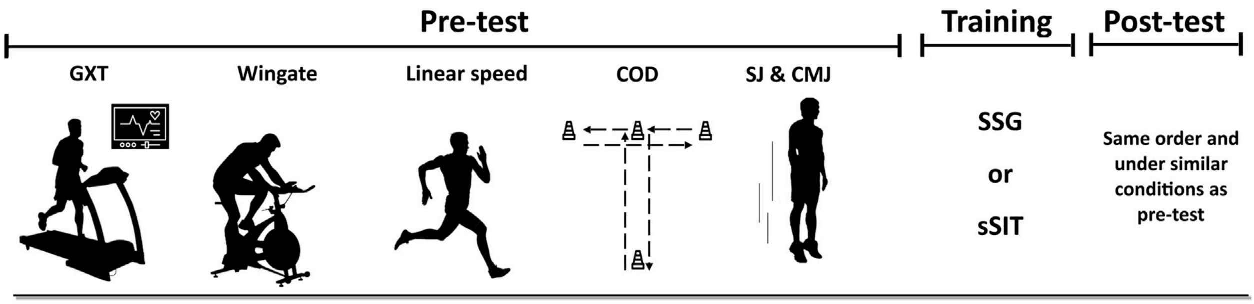

FIGURE 1
Overview of the experimental protocol. GXT, graded exercise test; COD, change of direction; SJ, squat jump, CMJ, countermovement jump; SSG, small-sided game; sSIT, short sprint interval training.

2.2 Participants

Twenty-four male well-trained soccer players [two goal keepers, six right and left fullbacks, four center backs, eight midfielders (center and wing), and four forwards] provided written informed consent and voluntarily participated. Participants were members of a provincial-level club with a soccer-playing experience of at least 10 years. Following the medical screening for any unknown complication or physical injury putting the participants at risk of high-intensity exercise, players were matched based on playing position and were randomized to either sSIT (Age = 25.8 ± 3.5 years; stature = 182 ± 2.9; Weight = 83.1 ± 4.8) or SSG (Age = 26.2 ± 4 years; stature = 180 ± 3.1; Weight = 84.9 ± 5.3) groups, each of 12. All players were familiar with all-out interval interventions but had not engaged in sSIT or SSG over the 3 months preceding this study. All procedures adhered to the ethical standards outlined in the Helsinki Declaration and were approved by the ethical committee of the University of Guilan, Iran.

2.3 Graded exercise test

After 10 min of warm-up consisting of 5 min of jogging and 5 min of dynamic stretching, athletes completed the graded exercise test on a treadmill (NordicTrack 1750, United States). The test commenced with the initial intensity of 8 km·h^{-1}, and velocity incrementally increased by 1 km h^{-1} every 3 min. Stages were separated with 30 s of relief intervals during which the blood lactate concentration was measured by earlobe blood sampling. During the test, a breath-by-breath gas collection system (MetaLyzer 3B-R2, Cortex, Germany) continuously measured cardiorespiratory fitness measures. $\dot{V}O_{2\,max}$ was verified if at least three of the following criteria were met: a) plateau or a slight drop in $\dot{V}O_2$ despite increasing workload; B) respiratory exchange ratio (RER) exceeding 1.1; C) attaining ≥90% age-predicted heart rate; D blood lactate concentration reaching 8 mmol l^{-1}; E) visible exhaustion (Sheykhlouvand et al., 2015; Sheykhlouvand and Forbes, 2017; Dai and Xie, 2023). VT_1 was defined as the point at which there was a raise in $\dot{V}_E/\dot{V}O_2$ and end-tidal O_2 tension ($P_{ET}O_2$) occurred without a simultaneous elevation in $\dot{V}_E/\dot{V}CO_2$. The criterion for identifying VT_2 was the sustained increase in both the $\dot{V}_E/\dot{V}O_2$ and $\dot{V}_E/\dot{V}CO_2$ ratio curves, correlated with the decrease in $P_{ET}O_2$ (Fereshtian et al., 2017; Alejo et al., 2022; Dai and Xie, 2023). Also, cardiac output (CO) and stroke volume (SV) were non-invasively measured using impedance cardiography (PhysioFlow, Manatec, France). Electrodes of the device were placed on the neck (two electrodes), xiphoid sternum (two electrodes), and one on each side of the chest. Following 20 s of calibration, cardiac hemodynamics were continuously measured during the test (Sheykhlouvand et al., 2022).

2.4 Lower-body Wingate test

Participants underwent a 30-s all-out Wingate test to determine their peak power output (PPO) and average power output (APO). At the start of the test, participants were directed to pedal against the inertial resistance of the ergometer (894E, Monark, Sweden) at their maximum speed. Following that, a resistance corresponding to 0.075 kg/kg of body mass was imposed, and the electronic revolution counter was initiated. Continuous verbal encouragement was given during the test, and PPO and APO were computed using the device's software.

2.5 Jumping ability

To assess jumping ability, tests for vertical jump (VJ) and countermovement jump (CMJ) were conducted utilizing a Globus electronic contact mat system (Codognè, Italy). The maximum height reached was measured with a precision of 0.01 m. During VJ, participants positioned their hands on their hips, shoulders, and feet wide apart and flexed their knees to approximately a 90-degree angle for 3 s. Subsequently, they exerted maximum effort in executing a vertical jump (Ramirez-Campillo et al., 2013). For executing CMJ, participants were guided to place their hands on their hips, assume a stance with feet and shoulders spread widely apart, and execute a downward motion (without any constraints on the achieved knee angle) before engaging in a vertical jump with full effort (Ojeda-Aravena et al., 2021). Participants were directed to land in an upright position and bend their knees after landing. Each participant performed three trials of this task, with rest intervals of approximately 60 s between each trial. The trial yielding the best performance among the three attempts was chosen for further statistical analysis.

TABLE 1 Change in measures of cardiorespiratory fitness over time.

	SSG			sSIT	
	Pre	Post		Pre	Post
$\dot{V}O_{2max}$ (ml·kg^{-1}·min^{-1})	51.84 ± 2.6	53.87 ± 2.1		51.57 ± 2.6	54.46 ± 2.7
p-value	0.001†			0.0004†	
%Δ	3.9			5.6	
d	0.85			1.07	
CV of mean %Δ	38%			16%	
$\dot{V}_E$ (l·min^{-1})	159.7 ± 6.9	165.9 ± 7.0		160.6 ± 7.8	169.0 ± 8.1
p-value	0.002†			0.0006†	
%Δ	3.9			5.7	
d	0.89			1.05	
CV of mean %Δ	35%			17%	
VT_1 (% $\dot{V}O_{2max}$)	71.9 ± 3.1	74.7 ± 3.7		72.9 ± 3.7	76.9 ± 3.9
p-value	0.003†			0.0001†	
%Δ	3.9			5.4	
d	0.82			1.05	
CV of mean %Δ	48%			14%	
VT_2 (% $\dot{V}O_{2max}$)	87.0 ± 3.2	90.0 ± 2.2		87.7 ± 3.0	91.3 ± 2.3
p-value	0.001†			0.0003†	
%Δ	3.4			4.1	
d	1.09			1.34	
CV of mean %Δ	61%			29%	
CO (l·min^{-1})	31.1 ± 1.5	32.4 ± 1.4		30.2 ± 1.7	31.8 ± 1.8
p-value	0.002†			0.0008†	
%Δ	4.2			5.3	
d	0.89			0.91	
CV of mean %Δ	48%			28%	
SV (ml·b^{-1})	156.2 ± 7.2	161.9 ± 6.6		160.5 ± 7.7	167.4 ± 6.6
p-value	0.008†			0.0001†	
%Δ	3.6			4.3	
d	0.82			0.96	
CV of mean %Δ	57%			32%	

Values are means ± SD; %Δ, within group changes from pre-to post-training.
CO, cardiac output; ES, effect size; SV, stroke volume; $\dot{V}O_{2max}$ maximum oxygen uptake; $\dot{V}_E$, maximal ventilation; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold. N = 10 for each group. † Significantly greater than pre-training value ($p < 0.05$).

2.6 Linear speed

Following a comprehensive warm-up, participants underwent two consecutive 20-m sprint tests with a 3-min rest interval to assess their linear speed. Participants were prompted to sprint between electronic timing gates (JBL Systems Oslo, Norway) at their maximum speed, choosing their own start time, with the time measured to the nearest 0.01 s. Upon readiness, the players commenced the run, starting from a stationary position behind the starting line. The trial exhibiting the highest performance level was selected for further statistical analysis.

TABLE 2 Change in measures of bio-motor abilities over time.

	SSG		sSIT	
	Pre	Post	Pre	Post
PPO (W)	873.3 ± 60.0	914.3 ± 55.2	889.7 ± 60.5	937.7 ± 59.8
p-value	0.007†		0.001†	
%Δ	4.7		5.4	
ES	0.71		0.81	
CV of mean %Δ	55%		24%	
APO (W)	541.5 ± 43.7	572.7 ± 45.6	543.8 ± 39.4	583.2 ± 39.3
p-value	0.004†		0.0004†	
%Δ	5.7		7.2	
ES	0.69		1.00	
CV of mean %Δ	47%		21%	
20-m sprint (s)	3.30 ± 0.04	3.19 ± 0.07	3.23 ± 0.08	3.04 ± 0.07
p-value	0.004†		0.0007†	
%Δ	−3.4		−6.2☐	
ES	0.92		1.52	
CV in mean %Δ	53%		28%	
COD (s)	7.90 ± 0.22	7.65 ± 0.20	7.91 ± 0.20	7.67 ± 0.21
p-value	0.002†		0.001†	
%Δ	−3.2		−3.1	
ES	1.19		1.17	
CV of mean %Δ	30%		28%	
SJ (cm)	38.4 ± 1.5	40.4 ± 1.2	38.6 ± 1.5	40.8 ± 1.6
p-value	0.005†		0.009†	
%Δ	5.2		5.6	
ES	1.47		1.42	
CV of mean %Δ	32%		29%	
CMJ (cm)	42.0 ± 1.0	44.2 ± 1.1	41.7 ± 1.2	44.0 ± 0.9
p-value	0.004†		0.002†	
%Δ	5.2		5.5	
ES	1.09		1.16	
CV of mean %Δ	24%		25%	

Values are means ± SD; %Δ, within group changes from pre-to post-training.
APO, average power output; COD, change of direction; CMJ, countermovement jump; ES, effect size; PPO, peak power output; SJ, squat jump. N = 10 for each group. † Significantly greater than pre-training value ($p < 0.05$); ‡ Significantly greater changes than the SSG ($p < 0.05$).

2.7 Change of direction

The evaluation of Change of Direction (COD) performance involved measuring multi-directional running speed, including linear sprints, shuffling to the right and left, and backpedaling, utilizing the MAT-test. This test is a modified version of the agility T-test. Due to the repeated sprints with direction changes over a short distance, MAT appears to be a more reliable and sport-specific measure of agility compared to the T-test (Sassi et al., 2009).

2.8 SSG and sSIT protocols

The players followed their regular soccer off-season training schedule, engaging in tactical drills, technical exercises, and

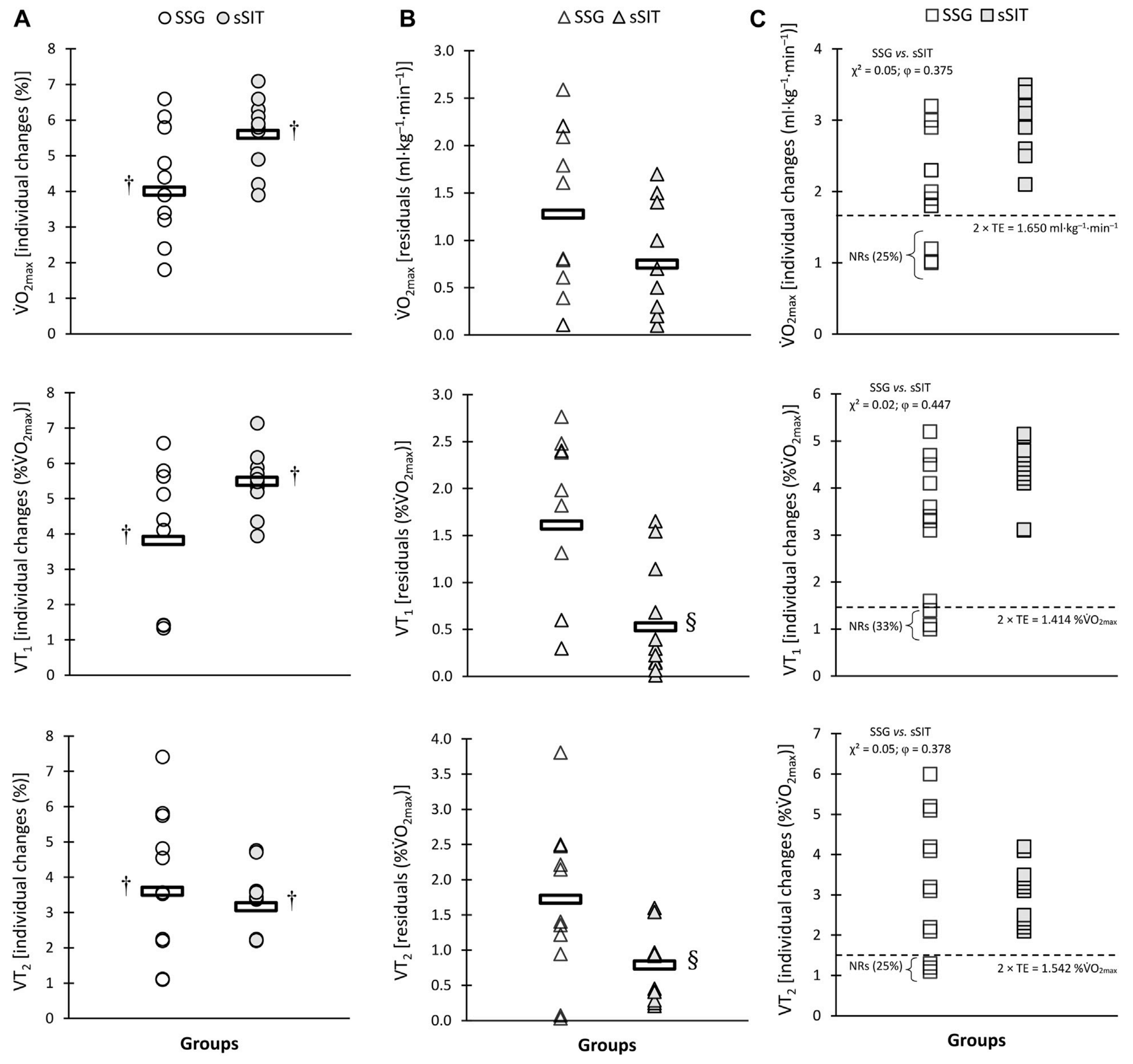

FIGURE 2
Individual percent change **(A)**, residuals in individual changes **(B)**, and proportions of non-responders **(C)** to small-sided game (SSG) and short sprint interval training (sSIT) over the training period. $\dot{V}O_{2max}$, maximum oxygen uptake; VT_1, first ventilatory threshold; VT_2, second ventilatory threshold. † Significantly greater than pre-training value. § Significantly lower than SSG group.

simulated competitive games, five sessions per week. These sessions typically lasted between 60 and 70 min, from 4:00 to 6:00 P.M. sSIT and SSG were completed before the regular soccer training program on Sunday, Monday, and Wednesday. The training was initiated with ~5 min of jogging, 5–10 min of dynamic movements, and sprinting with the integration of soccer-specific technical actions. Following the warm-up, participants of the sSIT group executed 3 sets of 10 × 4 s all-out sprints with 20 s of recovery between efforts and 3 min of rest intervals between sets. The SSG comprised 3 sets of time-matched (4 min each) 3 v 3 efforts in a 20 × 15 m area with 3 min of relief between efforts. SSG was executed without a goalkeeper, while two coaches encouraged players and supplied new balls to maintain the game's flow. Teams were balanced according to the participants' playing positions. The game's objective was to maintain possession of the ball as long as possible (Hill-Haas et al., 2011; Dellal et al., 2012)

2.9 Statistical analysis

Data are presented as mean ± SD. The normality of distribution was assessed through the Shapiro-Wilk test, while Levene's test was employed to evaluate the homogeneity of variances. A two-factor mixed analysis of variance with the between factor [group (SSG & sSIT)] and repeated factor [trial (pre-training & post-training)] analyzed the data. Main effects or significant interactions were subsequently analyzed using Tukey's post-hoc. Inter-individual variability in the adaptive changes was measured using three

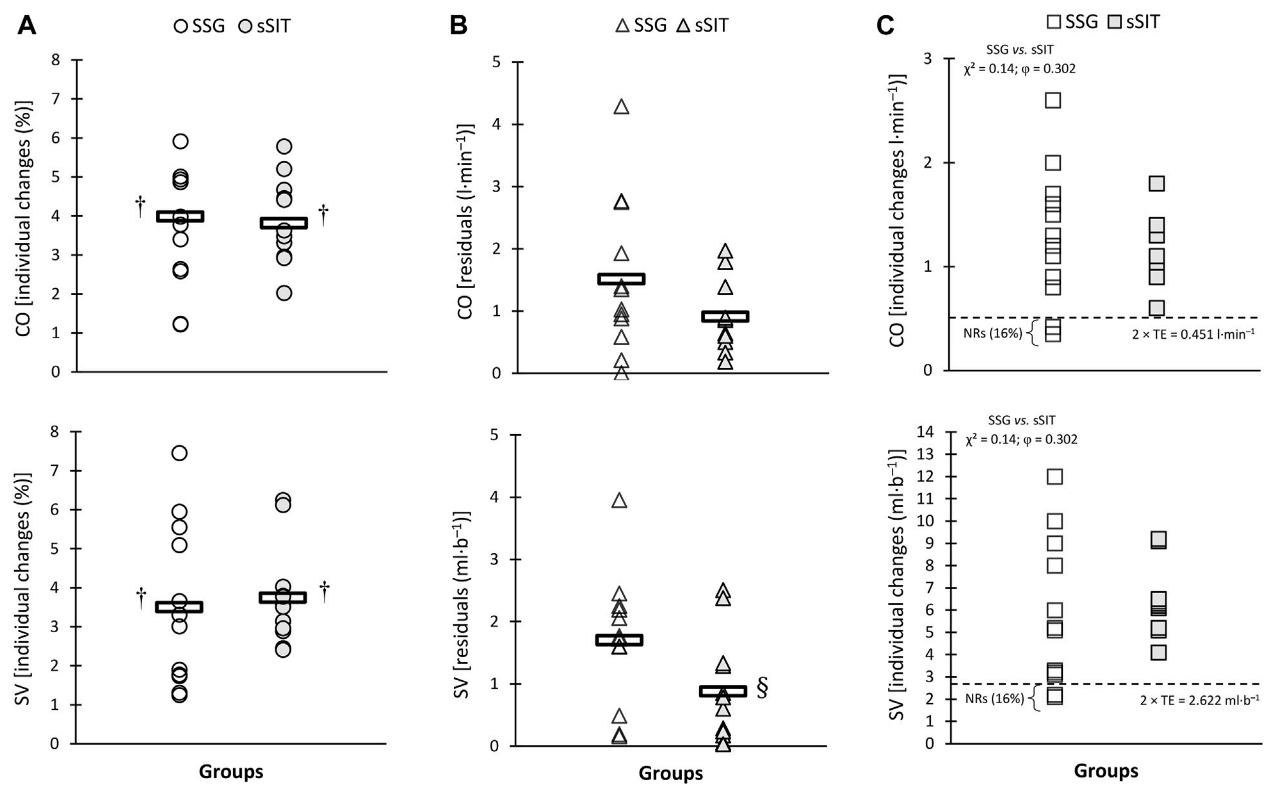

FIGURE 3
Individual percent change **(A)**, residuals in individual changes **(B)**, and proportions of non-responders **(C)** to small-sided game (SSG) and short sprint interval training (sSIT) over the training period. CO, cardiac output; SV, stroke volume. † Significantly greater than pre-training value. § Significantly lower than SSG group.

methods. First, individual percent changes from pre-to post-training were calculated for each variable, and the coefficient of variations (CVs) in the adaptive changes was determined as the ratio of SD to mean individual percent changes. Second, individual residuals in percent changes were calculated as the squared root of the squared difference between the individual percent change and the mean percent change for each tested variable, and the group mean residuals for each intervention were compared between SSG and sSIT interventions to determine their effects on inter-subject variability in the magnitude of the adaptations. Third, technical error (TE) was calculated for each variable ($TE = SD_{diff}/\sqrt{2}$) (Hopkins, 2000) to determine responders (Rs) and non-responders (NRs) to the interventions. In accordance with Hopkins (2000), a change greater than 2 × TE was representative of a high probability (with odds of 12 to 1) that the observed response is an actual physiological adaptation beyond what could reasonably be ascribed to technical or biological fluctuations. NRs were characterized as individuals unable to exhibit a notable increase or decrease (favoring beneficial changes) in the measured variables exceeding 2 × TE from zero (Ramirez-Campillo et al., 2018). TEs were as follows [$\dot{V}O_{2\,max}$, 0.825 (ml·kg^{-1}·min^{-1}) × 2; VT_1, 0.707 (% $\dot{V}O_{2\,max}$) × 2; VT_2, 0.771 (% $\dot{V}O_{2\,max}$) × 2; CO, 0.225 (l min^{-1}); SV, 1.311 (ml·b^{-1}) × 2; PPO, 12.675 (W) × 2; APO, 9.205 (W) × 2; SJ, 0.575 (cm) × 2; CMJ, 0.463 (cm) × 2; 20-m sprint, 0.020 (s) × 2; and COD, 0.069 (s) × 2]. Finally, The Chi-Square test (χ^2) was utilized to compare groups of participants falling within the two times the typical error (2 × TE) range calculated for each outcome (NRs) or those exceeding it by more than two times the typical error (Rs). Statistical analyses were carried out using SPSS software, version 25.0 (IBM Corp., Chicago, IL), and the alpha level was set at 0.05.

3 Results

At the baseline, no between-group difference was observed for the measured physiological and anthropometric measures. Both SSG and sSIT significantly enhanced bio-motor abilities and cardiorespiratory fitness measures over time (Tables 1, 2). A significant time-regimen interaction was found in linear speed. The change in 20-m sprint time in response to sSIT was significantly greater (p = 0.005; 95% CI: 0.030–0.146) than that of SSG.

After the 6-week training period, a significant time-regimen interaction ($p \leq 0.05$) was found in residuals of individual changes in VT_1, VT_2, SV, PPO, and APO. As shown in Figures 2–4, sSIT resulted in lower residuals in individual changes in VT_1 (p = 0.003; 95% CI: 0.419–1.752), VT_2 (p = 0.012; 95% CI: 0.245–1.798), SV (p = 0.048; 95% CI: 0.008–1.642), and PPO (p = 0.007; 95% CI: 0.357–1.966) compared to SSG. Moreover, except for SJ and CMJ, the coefficient of variations in mean percent changes in response to sSIT were lower than those of SSG (Tables 1, 2). Moreover, SSG showed 25%, 33%, 25%, 16%, 16%, 33%, and

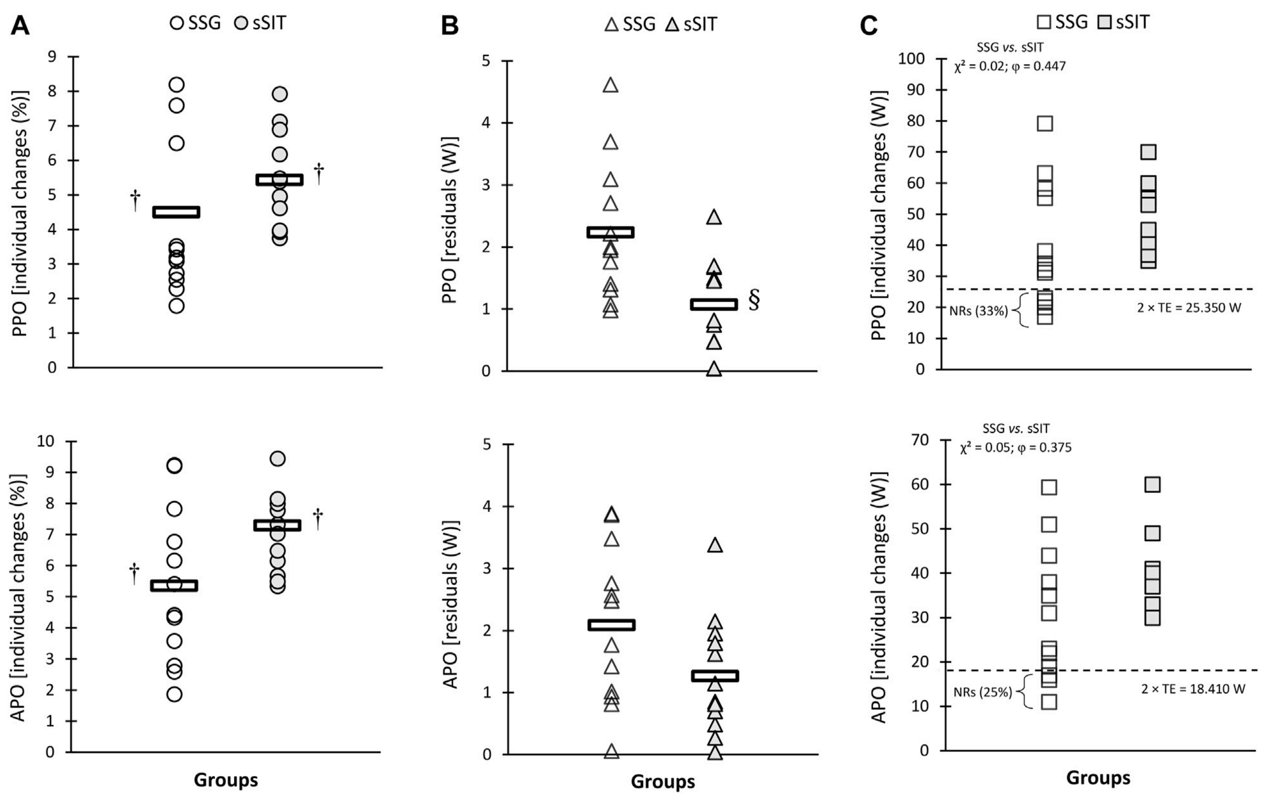

FIGURE 4
Individual percent change **(A)**, residuals in individual changes **(B)**, and proportions of non-responders **(C)** to small-sided game (SSG) and short sprint interval training (sSIT) over the training period. PPO, peak power output; APO, average power output. † Significantly greater than pre-training value. § Significantly lower than SSG group.

25% non-responders in $\dot{V}O_{2\,max}$, VT_1, VT_2, CO, SV, PPO, and APO, respectively (Figures 2–4). χ^2 test indicated lower responders to SSG in $\dot{V}O_{2\,max}$ ($p = 0.05$, $\varphi = 0.375$), VT_1 ($p = 0.02$, $\varphi = 0.447$), VT_2 ($p = 0.05$, $\varphi = 0.378$), PPO ($p = 0.02$, $\varphi = 0.447$), and APO ($p = 0.05$, $\varphi = 0.378$) than sSIT (Figures 2, 4). No between-group difference was found in the residuals of the adaptations and proportions of responders in linear speed, change of direction, and jumping ability (Figures 5, 6).

4 Discussion

This study compared the homogeneity of the adaptations to small-sided games versus short sprint interval training by evaluating inter-individual variability in adaptive responses of cardiorespiratory fitness and bio-motor abilities in soccer players. Both SSG and sSIT interventions adequately stimulated the adaptive mechanisms, enhancing qualities mentioned above. The most remarkable findings of this study were that, when comparing inter-individual variability in terms of residuals in the magnitude of the changes over the 6-week training period, sSIT resulted in more uniform adaptations in VT_1, VT_2, SV, and PPO than SSG. From a "responders and non-responders" point of view, SSG indicated significantly greater proportions of non-responders in $\dot{V}O_{2\,max}$, VT_1, VT_2, PPO, and APO than sSIT. In addition, except for jumping ability, the coefficient of variations in mean group changes in response to sSIT was lower than those of SSG.

Our study stands as the first endeavor to investigate how adaptations manifest in response to the small-sided game and sprint interval training multi-dimensionally and to provide a clear picture of individual adaptive responses to external stimuli imposed by these interventions. Our results corroborate previous studies indicating remarkable heterogeneity in individual adaptations to different forms of interval interventions (Dai and Xie, 2023; Wang and Zhao, 2023; Luo et al., 2024). Divergence in the adaptations around mean alludes to inter-subject variation in the adaptive response to training intervention, a phenomenon frequently observed yet explicitly addressed in only a relatively small number of studies. At both ends of a spectrum representing individual responses, there are individuals who exhibit notably significant responses (high Rs) and those who demonstrate notably small responses (low Rs) to a given training intervention (Mann et al., 2014). Nevertheless, individuals exhibiting a limited response to an exercise intervention in one parameter (e.g., $\dot{V}O_{2\,max}$) may not necessarily demonstrate the same response in other parameters (Vollaard et al., 2009; Scharhag-Rosenberger et al., 2012). This complexity further complicates the concept of high responders versus low responders. Previous studies attribute heterogeneous adaptations to divergent physiological profiles, genotype, baseline phenotype, training status, nutritional

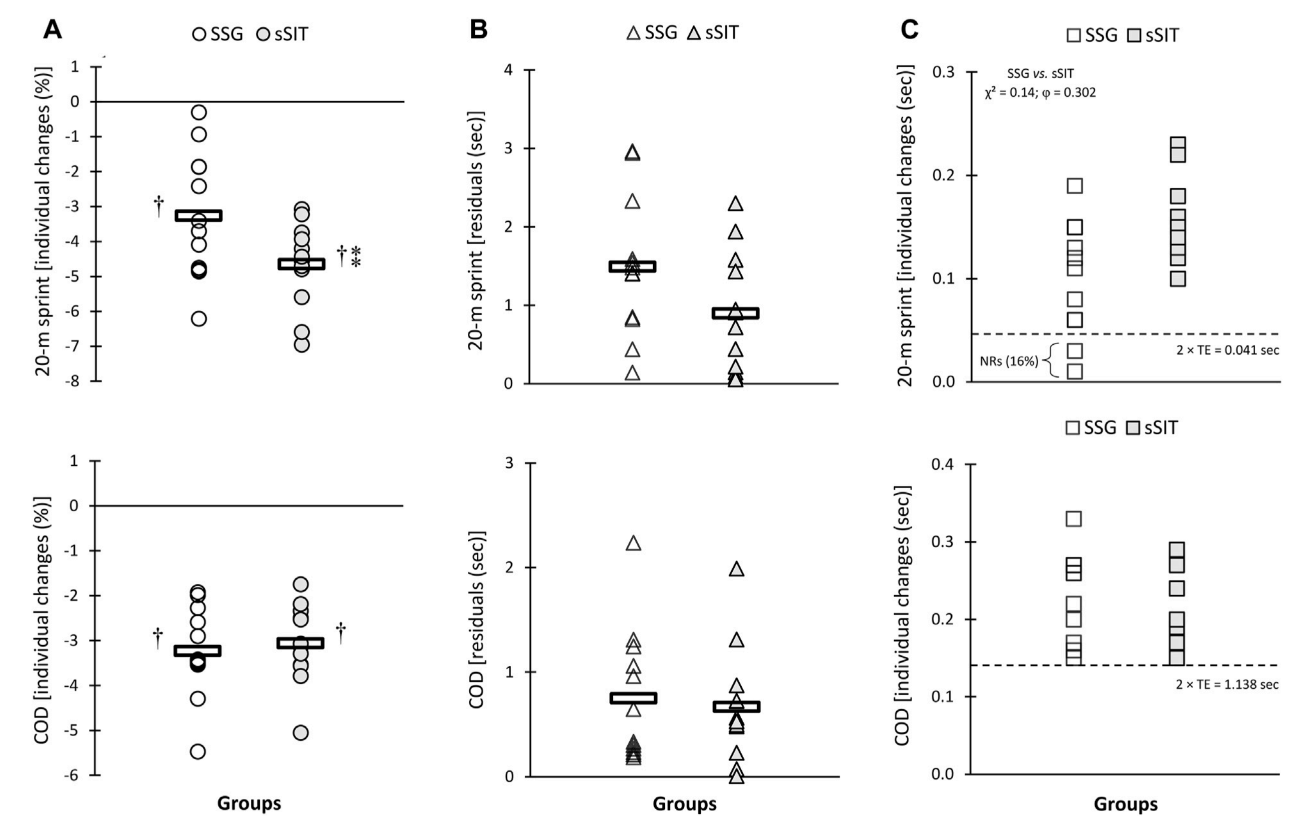

FIGURE 5
Individual percent change **(A)**, residuals in individual changes **(B)**, and proportions of non-responders **(C)** to small-sided game (SSG) and short sprint interval training (sSIT) over the training period. COD, change of direction. † Significantly greater than pre-training value. ‡ Significantly greater than SSG group.

strategies, sleep and stress, and fixed vs. flexible training prescription (Mann et al., 2014).

When comparing SSG and sSIT, it is essential to consider the homeostatic stress imposed by the training sessions, in addition to the mentioned parameters above. A game is a dynamic system formed by the interplay between two teams amid diverse contextual factors (Gréhaigne et al., 1997). Accordingly, all training scenarios encompass a certain degree of unpredictability, and this inherent unpredictability naturally contributes to an increase in the variability of stimuli (Hill-Haas et al., 2008a). A resulting source of variability in physiological demands may lead to different degrees of adaptations (Clemente et al., 2020). The collective homeostatic stress during an exercise session is influenced by factors like exercise intensity and duration, acting as a "stimulus" that triggers adaptive responses (Mann et al., 2014). "At the cellular level, adaptation to exercise training results from the cumulative impact of specific transcriptional and translational "micro-adaptations" occurring after each exercise session (Flück, 2006). Consequently, differences in the acute exercise stimulus received may account for individual variations in the training responses accumulated over time (Mann et al., 2014)." To modify such heterogeneity, researchers employ different reference intensities such as proportions of $\dot{V}O_{2\,max}$, MHR, anaerobic speed reserve, and different durations tailored to individual exercise tolerance or characteristics of the game in which the athlete competes. While these methods generate almost similar homeostatic stress levels across individuals with varying physiological capacities, they do not necessarily standardize all aspects of influencing parameters (McPhee et al., 2010). Research indicates that at higher intensities, lower variability in measured physiological parameters occurs (Bagger et al., 2003), and by exercising at higher absolute intensities, participants are likely to control their exercise intensity within a closer bandwidth (O'Grady, 2021). Accordingly, we utilized the upper limit of supramaximal intensity (*all-out*) for performing sSIT to fully engage individuals' capacity. By doing so, all factors influencing the utilization of the proportions of an individual's physiological and locomotor capacities are considered. As a result, athletes underwent the same proportion of their capacity (100%) and encountered equivalent homeostatic stress. However, SSG failed to modify the abovementioned parameters, resulting in a considerable variation in the adaptive responses.

Another important finding of this study was the significant effects of sSIT and SSG on enhancements of cardiorespiratory fitness and bio-motor abilities. Enhancements in cardiorespiratory fitness could be attributed to either an increase in the oxygen delivery (i.e., central component) or the improved ability of the active muscles to utilize delivered oxygen (i.e., peripheral component) (Sheykhlouvand et al., 2016a; Sheykhlouvand et al., 2016b; Sheykhlouvand et al., 2018a; Rasouli Mojez et al., 2021; Sayevand et al., 2022).

The rise in stroke volume and cardiac output following sSIT and SSG could partially contribute to improving of the central

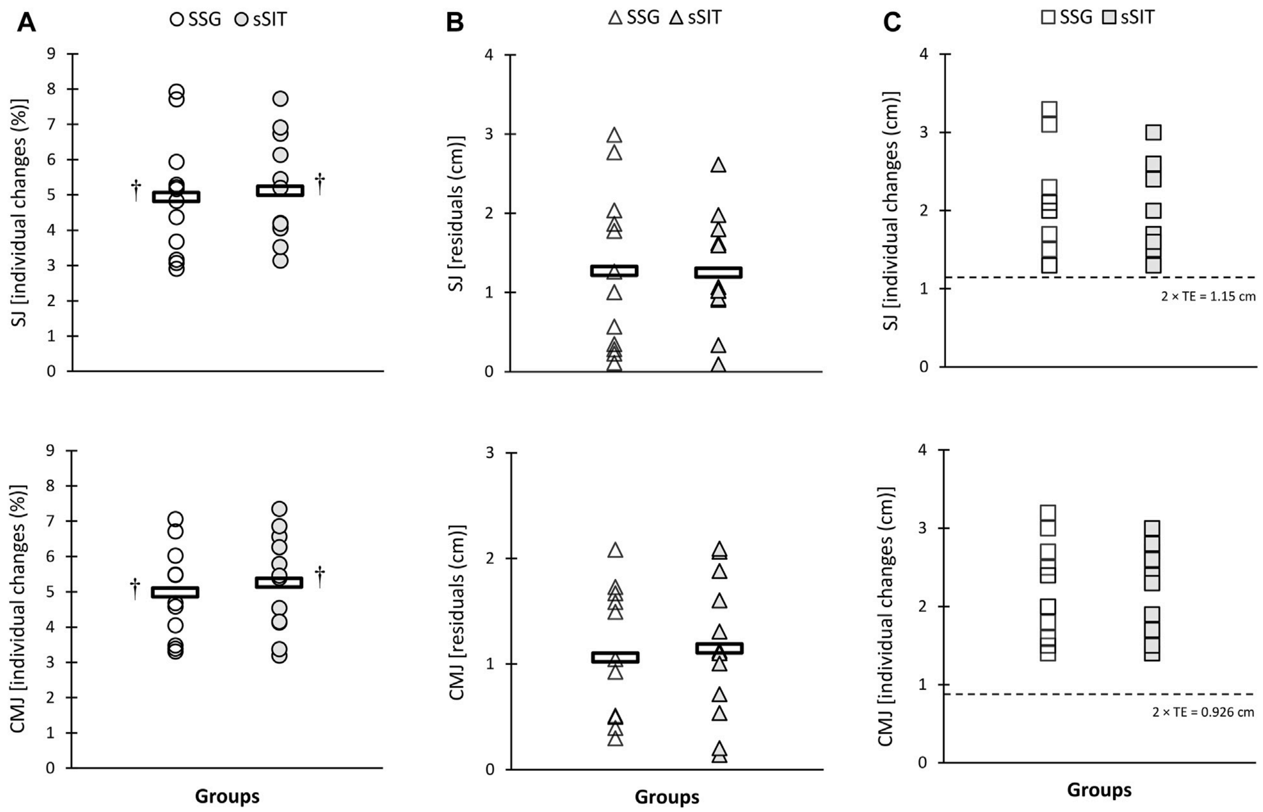

FIGURE 6
Individual percent change **(A)**, residuals in individual changes **(B)**, and proportions of non-responders **(C)** to small-sided game (SSG) and short sprint interval training (sSIT) over the training period. SJ, squat jump; CMJ, countermovement jump. † Significantly greater than pre-training value.

component of cardiorespiratory fitness. Our findings additionally validate the efficacy of both interval interventions in enhancing Wingate-based anaerobic power and jumping ability, the latter indicative of muscular power. Potential explanations for the enhanced anaerobic power may involve an increased discharge rate and recruitment of high-threshold motor units (Dolci et al., 2020), elevated total creatine content in active muscles (Hoffmann et al., 2020), and an improved buffering capacity of muscles (Sheykhlouvand et al., 2018b). Linear speed and change of direction also significantly improved in both groups. Notably, the magnitude of changes in 20-m sprint time in response to sSIT was significantly greater than in SSG, possibly due to the repeated generation of sprints during sSIT. A quick COD may arise from rapid force development and high power generation by the lower extremities (Miller et al., 2006). The improved linear speed can be attributed to enhancements in the acceleration component of maximal sprinting and improvements in stride length, contributing to overall sprint gains (Lee et al., 2020).

One potential limitation of this study is the exclusive inclusion of male participants, which restricts the generalizability of the findings solely to males, not females. Additionally, our capacity to closely supervise participants' sleep quality and rigorously monitor dietary habits was limited. It is essential to highlight that our results are related explicitly to interval protocols conducted under the conditions of this study. The potential for similar outcomes with other reference intensities or training volumes remains unknown.

5 Conclusion

In conclusion, this study compared the homogeneity of bio-motor abilities and cardiorespiratory fitness adaptations to small-sided games and short sprint interval training. Both recruited protocols adequately stimulated the mechanisms responsible for enhancing measures representing the abovementioned qualities. Comparing inter-individual variability in the adaptive changes by analyzing residuals in individual adaptations indicated that sSIT induces more uniform changes in VT_1, VT_2, SV, and PPO across team members than SSG. SSG also yielded lower responders in $\dot{V}O_{2\,max}$, VT_1, VT_2, PPO, and APO compared to sSIT. Additionally, excluding jumping ability, the coefficient of variation in mean group changes in response to sSIT was lower than in SSG.

6 Practical applications

Our findings indicated that 6 weeks of short sprint interval training facilitates more homogenous adaptations in measures of cardiorespiratory fitness and anaerobic power compared to a time-matched small-sided game. Imposing a uniform external load to elicit the same degrees of adaptive responses across team members is one of the crucial objectives of preparatory programs. Although SSG considers the game's technical and tactical aspects, it fails to impose external load on team members consistently. Hence, when the objective of the intervention is to uniformly enhance aerobic and anaerobic qualities across team members, it is recommended that sSIT be incorporated into regular soccer training under the conditions of this study.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the Ethical committee of the University of Guilan, Iran. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MG: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Visualization, Writing–review and editing.

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Comparison of acute physiological responses between one long and two short sessions of moderate-intensity training in endurance athletes

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Purpose: To compare acute physiological responses and perceived training stress between one long and two short time- and intensity-matched sessions of moderate-intensity training in endurance athletes.

Methods: Fourteen male endurance athletes (VO_{2max}: 69.2 ± 4.2 mL·min^{-1}·kg^{-1}) performed one 6 × 10-min interval session (SINGLE) and two 3 × 10-min interval sessions interspersed with 6.5 h recovery (DOUBLE) of moderate-intensity training on two separate days, while running in the laboratory, using a counterbalanced cross-over trial. The two training days were separated into a first part/session (interval stage 1–3) and second part/session (interval stage 4–6). Respiratory variables, heart rate (HR), blood lactate concentrations (BLa), and rating of perceived exertion (RPE) were collected during sessions, whereas supine heart rate (HR) was assessed in a 60-min recovery period following sessions. Measures of perceived training stress (1–10) were assessed in the morning of the subsequent day.

Results: HR, Bla, and RPE increased in the second compared to first part of SINGLE (168 ± 7 vs. 173 ± 7 bpm, 2.60 ± 0.75 vs. 3.01 ± 0.81 mmol·L^{-1}, and 13.4 ± 1.0 vs. 14.8 ± 1.1-point, respectively, all $p < 0.05$). HR and Bla decreased in the second compared to first session of DOUBLE (171 ± 9 vs. 166 ± 9 bpm and 2.72 ± 0.96 vs. 2.14 ± 0.65 mmol·L^{-1}, respectively, both $p < 0.05$). SINGLE revealed higher supine HR in the recovery period following sessions (65.4 ± 2.5 vs. 60.7 ± 2.5 bpm $p < 0.05$), session RPE (sRPE, 7.0 ± 1.0 vs. 6.0 ± 1.3-point, $p = .001$) and sRPE training load (929 ± 112 vs. 743 ± 98, $p < 0.001$) compared to DOUBLE. In the subsequent morning, increased levels of perceived fatigue and muscle soreness were observed following SINGLE compared to DOUBLE (7.0 ± 2.5 vs. 8.0 ± 1.0-point, $p = .049$ and 6.0 ± 2.5 vs. 7.0 ± 2.5-point, $p = .002$, respectively).

Conclusion: One long moderate-intensity training session was associated with a duration-dependent "drift" in physiological responses compared to two short time- and intensity-matched sessions, thereby suggesting a higher overall training stimulus. Simultaneously, the lower cost of the two shorter sessions indicates that such organization could allow more accumulated time at this intensity. Overall, these findings serve as a starting point to better understand the pros and cons of organizing moderate-intensity training as one long versus shorter sessions performed more frequently (e.g., as "double threshold training") in endurance athletes.

KEYWORDS

cardiovascular drift, durability, endurance sport, threshold training, training characteristics, training intensity

Introduction

Endurance exercise performance is primarily limited by the athlete's maximal oxygen uptake (VO_{2max}), fractional utilization of VO_{2max} [indicated by e.g., lactate/ventilatory "thresholds" or performance oxygen uptake (VO_2)], and work economy/efficiency (Joyner and Coyle, 2008). To provide a stimulus for improving endurance performance, a sufficient training load must be achieved through the interaction between training volume, intensity, and frequency. Retrospective analyses of elite to world-class endurance athletes have reported annual training volumes ranging from 500 to 1,200 h depending on the sport-specific demands, with most training performed as low intensity (~70–90%), supplemented by 10%–30% as moderate- to high-intensity training (Seiler, 2010; Stöggl and Sperlich, 2015; Sperlich et al., 2023; Staff et al., 2023). Although most scientific literature emphasizes the effects and underlying mechanisms of high-intensity training (Laursen and Jenkins, 2002; Laursen, 2010; Stöggl and Sperlich, 2015), endurance athletes, and particularly elite endurance athletes, perform surprisingly small volumes of high-intensity training and often substantially larger volumes of both low- and moderate-intensity training (Burnley et al., 2022; Haugen et al., 2022; Casado et al., 2023; Sandbakk et al., 2023).

Moderate-intensity training is performed between the first and second lactate/ventilatory "threshold" and therefore often referred to as "threshold training" (Seiler, 2010). This type of training can be performed both as continuous sessions and as intervals with relatively long work duration. In this context, an increasingly popular method adopted across different endurance sports is so-called "double-threshold training," which means that two "threshold sessions" are performed on the same day (Bakken, 2022; Casado et al., 2023), with "easy days" of low-intensity training in between. Although there is limited scientific literature to support the use of "double-threshold training," information from sports practice indicates that the method originates from, and is currently well established in middle- and long-distance running (Tjelta, 2019; Casado et al., 2023; Kelemen et al., 2023). Although the volume of each session is often reduced compared to performing one longer session, the aim is normally to increase the accumulated time at relatively high, competition-specific intensities. The internal exercise intensity during such sessions, is typically around 82%–87% of maximal heart rate (HR_{max}), 2–4 mmol·L^{-1} in blood lactate concentrations (Bla), and 12–16 in rating of perceived exertion (RPE) using the 6–20-point Borg scale (Seiler, 2010; Bakken, 2022; Casado et al., 2023).

Previous studies have speculated that higher overall volume of moderate-intensity training effectively drives positive adaptations related to the primary performance-determining factors in middle- and long-distance running (Bakken, 2022; Kelemen et al., 2023). In addition, lower injury risk through reduced mechanical loading combined with lower metabolic and autonomic disturbance per session (i.e., reduced recovery time) could be beneficial when performing two shorter sessions compared to one longer session (Bakken, 2022; Casado et al., 2023). However, another approach might be to split a long moderate-intensity session into two shorter sessions to allow a compensatory higher speed or power output and, thereby obtain higher external intensity/load at the same internal intensity/load [i.e., Bla, RPE, and heart rate (HR)] (Bakken, 2022; Casado et al., 2023). Although different approaches and potential benefits of performing two shorter sessions compared to one longer moderate-intensity session may exist, further examination is required to elucidate the underlying mechanisms.

In contrast, the benefits of performing fewer, but longer sessions at moderate intensity may include a larger acute training stimulus caused by greater work per session and a duration-dependent "drift" in internal intensity measures, which is speculated to upregulate molecular signaling and subsequent adaptations (Seiler, 2010; Maunder et al., 2021). Such changes in internal intensity-measures have previously been observed during prolonged sessions of low intensity endurance training in well-trained cyclists (Rønnestad et al., 2011; Hopker et al., 2017). It has also been shown that "drift" in internal intensity measures associated with performing one long compared to two shorter distance-matched sessions at low-intensity in national-level cross-country skiers influences subsequent measures of perceived training stress (Talsnes et al., 2022). However, the question is probably not whether "double-threshold training" is superior to one single session or vice versa, but rather to understand their different signal-to-stress ratios and choose the best tool at the right time for the purpose of maximizing adaptations and performance development. Taken together, despite information from sports practice emphasizing beneficial "effects" of adopting "double-threshold training" in elite to world-class endurance athletes (Bakken, 2022; Casado et al., 2023), the method has received little attention in the scientific literature. While training intervention studies are evidently required to investigate the actual training effects, descriptive studies on acute physiological responses at the same external intensity might be a starting point to better understand load and recovery differences between these types of organizing moderate-intensity ("threshold") training.

Therefore, the present study compared acute physiological responses and perceived training stress between one long and two short time- and intensity-matched sessions of moderate-intensity training in endurance athletes. It was hypothesized that performing one long session would induce higher overall physiological responses and perceived training stress compared to two time- and intensity-matched short sessions.

Methods

Participants

Fourteen trained male endurance athletes (national-level cross-country skiers, n = 11 and runners, n = 3) volunteered to take part in the study. Physiological and anthropometrical characteristics of the group are presented in Table 1. The inclusion criteria specified that participants had to be between 18–35 years of age, that they perform at least 5 endurance training sessions per week, with more than 5 years experience of endurance training and without any major interruption due to injury or illness. The participants were not familiar with performing "double-threshold training" prior to the study although all participants were familiar with running in relatively steep uphill's. The Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for such studies. Therefore, the study was approved by the Norwegian Centre for Research Data and conducted in accordance with the institutional requirements and the Declaration of Helsinki. All participants gave their oral and written consent before participation.

Design

The study was a counterbalanced cross-over trial in which the participants reported to the laboratory on three separate occasions. Initially, preliminary physiological testing was performed within 2 weeks of the experimental trial as a part of the participants regular testing regimes. A preliminary test, including submaximal and maximal stages, was used to determine individual workloads for the subsequent moderate-intensity training sessions constituting the experimental trial. The experiment included two training days matched for the same time and external intensity consisting of either one 6 × 10-min interval session (SINGLE) or two 3 × 10-min interval sessions interspersed by 6.5 h of recovery in between (DOUBLE), conducted while running in the laboratory. In all analyses, SINGLE was separated into a first part (interval stage 1–3) and second part (interval stage 4–6), and DOUBLE separated into two sessions [first session (interval stage 1–3) and second session (interval stage 1–3)]. Respiratory variables, HR, Bla, blood glucose concentrations (BG), and RPE were collected during each session, whereas supine HR was assessed during a 60-min recovery period following each session. Different measures of perceived training stress and recovery were assessed both 15 min following each session and in the morning of the subsequent training day.

Preliminary physiological testing

The participants performed a blood lactate profile test followed by an incremental test to exhaustion, running at a 10.5% fixed incline using protocols previously described (Talsnes et al., 2021). The blood lactate profile test consisted of 5-min stages with increasing speeds (1 km·h^{-1}) until the participants reached a Bla value of >4 mmol·L^{-1}. Speed at 4 mmol·L^{-1} was calculated using linear interpolation The subsequent incremental test to exhaustion included increasing speeds by 1 km·h^{-1} every min until exhaustion, with a plate in VO_2 despite of increasing speed as the main criteria for achieving VO_{2max} (See Table 1 for data from the preliminary physiological test).

Experimental trial

The rationale for the experimental design and different sessions constituting SINGLE and DOUBLE were based on combination of verbal communication with coaches of elite- to world-class endurance athletes regularly performing "double-threshold training" and available scientific literature (Bakken, 2022; Casado et al., 2023) The experimental trial involved all participants, with half of them commencing with SINGLE and

TABLE 1 Anthropometrical characteristics and physiological tests of the fourteen male endurance athletes participating in the study.

Age (y)	23.1 ± 4.1
Body height (cm)	176.7 ± 4.2
Body mass (kg)	71.5 ± 8.3
Body mass index (kg·m^{-2})	22.9 ± 1.9
Incremental test to exhaustion	
VO_{2max} (mL·min^{-1})	4,896 ± 495
VO_{2max} (mL·min^{-1}·kg^{-1})	69.2 ± 4.2
HR_{max} (bpm)	196 ± 6
Blood lactate profile test (4 mmol·L^{-1})	
Speed at 4 mmol·L^{-1} (km·h^{-1})	10.7 ± 0.7
Speed at 90% of 4 mmol·L^{-1} (km·h^{-1})	9.6 ± 0.5
VO_2 at 4 mmol·L^{-1} (mL·min^{-1})	3,983 ± 511
VO_2 in % of VO_{2max} at 4 mmol·L^{-1}	82.1 ± 4.2

VO_{2max}, maximal oxygen consumption; HR_{max}, maximal heart rate; bpm, beats per minute; VO_2, oxygen uptake.

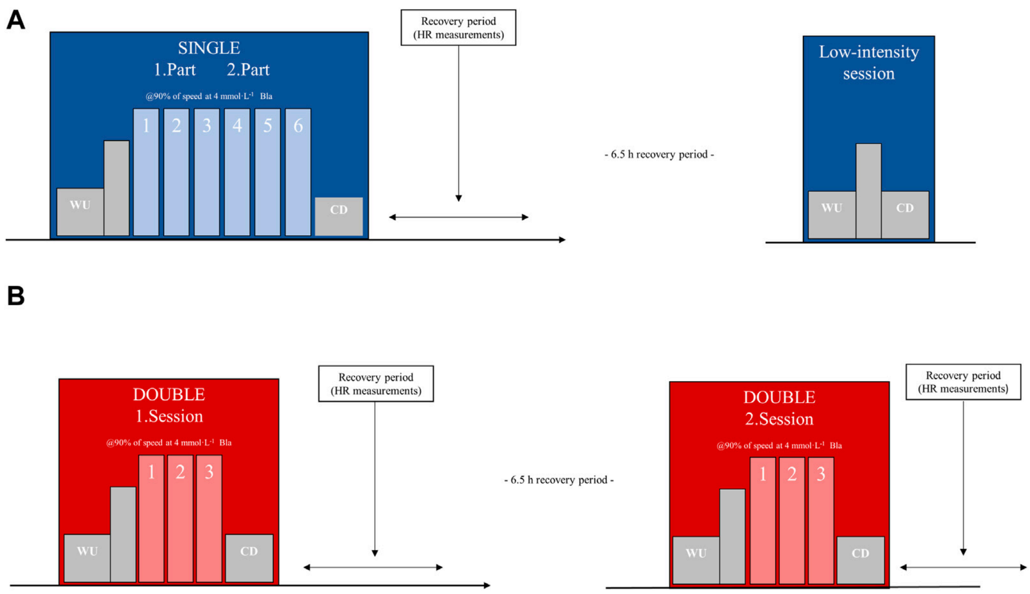

FIGURE 1
Complete protocol of the experimental trial consisting of **(A)** one 6 × 10-min interval session (SINGLE) and **(B)** two 3 × 10-min interval sessions interspersed with 6.5 h recovery (DOUBLE) of moderate-intensity training on two separate days, while running in the laboratory, using a counterbalanced cross-over trial. WU, warm-up; CD, cool-down; Bla, blood lactate concentrations; HR, heart rate.

the other half with DOUBLE on the first training day, respectively. The complete study protocol is shown in Figure 1. Both training days were time- and intensity-matched and conducted at the same external intensity, corresponding to 90% of the participants' speed at 4 mmol·L^{-1} from the preliminary blood lactate profile test. Based on extensive experience with physiological testing and verbal communication with sports practice, this external intensity was considered appropriate to elicit internal intensity measures that aligns with the use of "threshold training". SINGLE comprised one 6 × 10-min interval session, while DOUBLE consisted of two 3 × 10-min interval sessions interspersed with 6.5 h of recovery in between. The recovery time between each interval stage during sessions was set to 2 min. Before each session, participants underwent a 20-min standardized warm-up protocol, including 15 min at a fixed incline and speed (5% and 8 km·h^{-1}), followed by 5 min at the same incline as the intervals and a fixed speed (10.5% and 8 km·h^{-1}). Following completion of the intervals, participants underwent a standardized cool-down protocol comprising 15 min at a fixed incline and speed (5% and 8 km·h^{-1}). The relatively steep uphill was chosen for the purpose of the study in attempt to isolate physiological responses and decouple potential differences in running technique between participants. To time- and intensity-match the volume of both low- and moderate-intensity training across the two training days, a short low-intensity session (warm-up and cool-down protocol) was performed 6.5 h after SINGLE due to the additional warm-up and cool-down performed in connection with the second session of DOUBLE. The experimental trial was conducted in the laboratory under steady room temperature (17°C–19°C) and humidity (35%–45%). Participants were instructed to engage in low-intensity training exclusively during the last 2 days before the experimental trial and to replicate the same training regimen before both training days. The participants' average training volume (exclusively low-intensity training) over the last 2 days was 2.0 ± 0.9 h and 1.9 ± 0.8 h before the SINGLE and DOUBLE sessions, respectively.

Nutritional protocol

In best attempt to standardize nutritional status, the participants were instructed to replicate their dietary intake both the day before and the day constituting the experimental trial. During sessions, the participants consumed sports drink (Maxim, Orkla, Oslo, Norway) with the total fluid and carbohydrate (CHO) intake matched (1 L·h^{-1}) between the two training days. The amount of sports drink and CHO intake (70 g·h^{-1}) were according to ACSM guidelines on recommended CHO intake during endurance exercise (Rodriguez et al., 2009). In the 60-min recovery period following each session, the participants consumed a 185-kcal energy bar (New Energy, Nidar, Orkla, Trondheim, Norway) and a 100-kcal banana (BAMA Gruppen, Oslo, Norway) after 15 min, whereas water ad libitum were provided during the entire recovery period.

Physiological responses

Respiratory variables including VO_2, minute ventilation (VE), and respiratory exchange ratio (RER) were collected over the entire 10-min interval stages. HR was monitored continuously during sessions and in the subsequent 60-min recovery period. Bla, BG, and RPE were collected after each interval stage was completed.

Supine heart rate

As a measure of autonomic recovery, supine HR was quantified 15 min before and 15, 30, 45 and 60 min following each session during a 5-min period where the participants lied down on a gym mat in the laboratory. The participants average HR over the last minute of the 5-min period was used for analyses.

Measures of perceived training stress and recovery

Prior to each session, the participants reported their perceived "motivation" and "readiness" on a scale ranging from 1 (poor) to 10 (excellent). 15-min following each session, the participants gave their session RPE (sRPE) on a 1–10 scale. Internal training load was calculated by multiplying the participants sRPE by the duration of each session in minutes (Halson, 2014). The participants further gave their perceived training quality on a scale ranging from 1 (poor) to 10 (excellent) from a physical, technical, and mental perspective using the training quality scale recently developed by Shell et al. (2023). Lastly, measures of perceived training stress and recovery were reported in the morning of the subsequent training day including questions on sleep quality, general mental and physical wellbeing, readiness to train, muscle soreness, fatigue, and attractiveness to the training day from 1 (poor) to 10 (excellent) (Ten Haaf et al., 2017).

Equipment and materials

The experimental trial was performed on a 2.5 × 0.7-m treadmill (RL 3500E, Rodby, Vänge, Sweden). Respiratory variables were collected using open-circuit indirect calorimetry with mixing chamber (Vyntus CPX, CareFusion, Hoechberg, Germany). Bla and BG were taken from the fingertip of the participants and analyzed using the stationary Biosen C-Line lactate device (Biosen, EKF Industrial Electronics, Magdeburg, Germany). HR was recorded using a Garmin Forerunner 935 watch with electrode belt (Garmin Ltd., Olathe, KS, United States). RPE was determined using the 6–20-point Borg scale (Borg, 1970). The participants body masses and heights were measured using a medical weight and stadiometer (Seca model 708, Seca GmbH, Hamburg, Germany).

Statistical analyses

Data are reported as mean ± standard deviation (SD) for continuous variables and median ± interquartile range (IQR) for ordinal variables. Normality was checked using a combination of histograms and QQ-plots. A mixed linear model was used for analyses, specifically using the "lme4" package in R version 4.2.2 (R Development Core Team, Vienna, Austria). The model aimed to compare physiological responses between the two training days of different moderate-intensity training organization. The model included fixed effects for training day (SINGLE vs. DOUBLE) and part/session (first part/session vs. Second part/session) within the different training days. Additionally, the model included interactions between the fixed effects and a random effect specified for the participants variability. Where fixed effects were evident, Tukey post hoc comparisons were performed to assess specific differences. Further, measures of perceived training stress and recovery between SINGLE and DOUBLE were compared using the non-parametric Wilcoxon signed-rank test. Hedges g effect sizes were also calculated (Lakens, 2013) and interpreted as: 0.2–0.5 = small effect, 0.5–0.8 = moderate effect, and >0.8 large effect (Hopkins et al., 2009). The significance level for all comparisons was set at alpha levels of $p < 0.05$.

Results

Acute physiological responses

Data on acute physiological responses between moderate-intensity sessions are presented in Table 2 and Figures 2, 3. There was a 2.8% ± 1.8% higher HR (average across the different interval stages) in the second vs. First part of SINGLE, and −2.5% ± 2.3% lower HR in the second vs. First session of DOUBLE (all $p < 0.05$). Further, there was an interaction effect revealing 4.2% ± 2.8% higher HR in the second part of SINGLE vs. Second session of DOUBLE (all $p < 0.001$).

There were no significant differences either between or within SINGLE and DOUBLE in VO_2 although there was a 6.7% ± 3.5% higher VE (average across the different interval stages) in the second vs. First part of SINGLE. Further, there was an interaction effect revealing 4.9% ± 3.9% higher VE in the second part of SINGLE vs. Second session of DOUBLE (all $p < 0.001$). There was also an interaction effect revealing 0.025 ± 0.020 lower RER in the second part of SINGLE vs. Second session of DOUBLE (all $p < 0.05$).

There were 0.46 ± 0.50 $mmol \cdot L^{-1}$ and 0.54 ± 0.70 $mmol \cdot L^{-1}$ higher Bla and BG (average across the different interval stages) in the second vs. First part of SINGLE, as well as −0.59 ± 0.65 $mmol \cdot L^{-1}$ and −0.32 ± 0.44 $mmol \cdot L^{-1}$ lower Bla and BG in the second vs. First session of DOUBLE (all $p < 0.05$). Further, there were interaction effects demonstrating 0.91 ± 0.88 $mmol \cdot L^{-1}$ and 0.46 $mmol \cdot L^{-1}$ higher Bla and BG in the second part of SINGLE vs. Second session of DOUBLE (all $p < 0.001$). Lastly, there was a 1.4 ± 0.8-point higher RPE (average across the different interval stages) in the second vs. First part of SINGLE (all $p < 0.01$), as well as an interaction effect revealing 1.0 ± 0.7-point higher RPE in the second part of SINGLE vs. Second session of DOUBLE (all $p < 0.05$).

Supine heart rate

Supine HR responses in the subsequent recovery period were 7.8% ± 12.3%, 9.4% ± 13.4%, and 9.0% ± 13.7% higher 30, 45, and 60 min following SINGLE, respectively, compared to the average values of the two sessions constituting DOUBLE, (all $p < 0.05$, Figure 4). There were no significant differences between the first vs. Second session of DOUBLE.

TABLE 2 Acute physiological and perceptual responses to different organization of time- and intensity-matched moderate-intensity training in fourteen male endurance athletes.

	SINGLE		DOUBLE		SINGLE vs. DOUBLE	
	First part	Second part	First session	Second session	First part/session	Second part/session
Interval stage 1 (4)					ES (Hedges g)	
HR (bpm)	167 ± 8	173 ± 7*	167 ± 9	166 ± 8#	0.00	0.90
HR in $\%HR_{max}$	85.1 ± 2.8	88.3 ± 3.0	85.1 ± 3.8	84.6 ± 2.8	0.00	1.19
VO_2 ($mL \cdot min^{-1}$)	3,962 ± 433	4,078 ± 488	3,840 ± 500	3,829 ± 488	0.26	0.49
VE ($L \cdot min^{-1}$)	102 ± 12	111 ± 14*	101 ± 15	101 ± 14#	0.07	0.68
RER	0.92 ± 0.03	0.91 ± 0.04	0.92 ± 0.04	0.93 ± 0.03#	0.00	0.55
Bla ($mmol \cdot L^{-1}$)	2.49 ± 0.74	2.98 ± 0.82*	2.64 ± 0.94	2.17 ± 0.66*, #	0.16	1.04
BG ($mmol \cdot L^{-1}$)	4.78 ± 0.54	5.51 ± 0.63*	5.02 ± 0.65	4.84 ± 0.47#	0.39	0.85
RPE (6–20)	13.1 ± 0.8	14.5 ± 1.2*	13.6 ± 0.8	13.4 ± 0.8#	0.58	1.02
Interval stage 2 (5)						
HR (bpm)	170 ± 7	173 ± 7*	170 ± 9	165 ± 9*, #	0.00	0.96
HR in $\%HR_{max}$	86.6 ± 2.8	88.4 ± 3.0*	86.9 ± 3.9	84.4 ± 4.3*, #	0.08	1.04
VO_2 ($mL \cdot min^{-1}$)	4,031 ± 418	4,077 ± 443	3,908 ± 500	3,911 ± 508	0.26	0.33
VE ($L \cdot min^{-1}$)	106 ± 14	112 ± 14*	106 ± 18	104 ± 15#	0.00	0.52
RER	0.91 ± 0.03	0.90 ± 0.04	0.91 ± 0.04	0.92 ± 0.03#	0.00	0.50
Bla ($mmol \cdot L^{-1}$)	2.72 ± 0.82	3.03 ± 0.80*	2.80 ± 0.97	2.10 ± 0.63*, #	0.08	1.25
BG ($mmol \cdot L^{-1}$)	5.08 ± 0.40	5.53 ± 0.62*	5.45 ± 0.56	4.91 ± 0.39*, #	0.74	1.17
RPE (6–20)	13.3 ± 1.2	14.7 ± 0.9*	14.2 ± 1.0#	13.9 ± 1.0#	0.78	0.79
Interval stage 3 (6)						
HR (bpm)	171 ± 7	174 ± 7	172 ± 9	168 ± 9*, #	0.12	0.72
HR in $\%HR_{max}$	87.5 ± 2.8	88.7 ± 2.9	87.6 ± 4.0	85.9 ± 4.4*, #	0.01	0.45
VO_2 ($mL \cdot min^{-1}$)	4,052 ± 442	4,096 ± 464	3,947 ± 493	3,956 ± 510	0.21	0.26
VE ($L \cdot min^{-1}$)	109 ± 14	112 ± 14	108 ± 17	107 ± 17	0.06	0.30
RER	0.90 ± 0.04	0.90 ± 0.04	0.91 ± 0.04	0.92 ± 0.03#	0.22	0.48
Bla ($mmol \cdot L^{-1}$)	2.83 ± 0.93	2.90 ± 0.73	3.13 ± 1.23	2.62 ± 1.29	0.30	0.22
BG ($mmol \cdot L^{-1}$)	5.24 ± 0.76	5.32 ± 0.73	5.52 ± 0.61	5.17 ± 0.63	0.23	0.20
RPE (6–20)	13.8 ± 1.0	15.2 ± 0.9*	14.6 ± 1.0#	14.2 ± 1.2#	0.77	0.90

SINGLE, one 6 × 10-min "threshold interval session"; DOUBLE, two 3 × 10-min "threshold interval sessions"; ES, effect size; HR, heart rate; HR_{max}, maximal heart rate; VO_2, oxygen consumption; VE, minute ventilation; RER, respiratory exchange ratio; Bla, blood lactate concentrations; BG, blood glucose concentrations; RPE, rating of perceived exertion.
*Significant different from first part/session within SINGLE, and DOUBLE ($p < 0.05$).
#Significant different from SINGLE ($p < 0.05$).

Measures of perceived training stress and recovery

There was a −1.0 ± 0.5-point lower motivation in the second vs. First session of DOUBLE (p = .041, Table 3), with no other differences in perceived motivation and readiness before sessions reported. Further, no differences between SINGLE and DOUBLE in perceived training quality following sessions were reported, while higher sRPE and sRPE training load were evident for SINGLE compared to DOUBLE (−1.0 ± 0.7-point, p = .001 and 19.6% ± 9.3%, $p < 0.001$, respectively). In the morning of the subsequent training day, increased levels of perceived fatigue and muscle soreness were reported following SINGLE compared to DOUBLE (−1.0 ± 1.5, p = .049 and −1.0 ± 1.5, p = .002, respectively, Table 3).

Discussion

The present study compared acute physiological responses and perceived training stress between one long and two short time- and intensity-matched sessions of moderate-intensity training in endurance athletes. In accordance with our hypotheses,

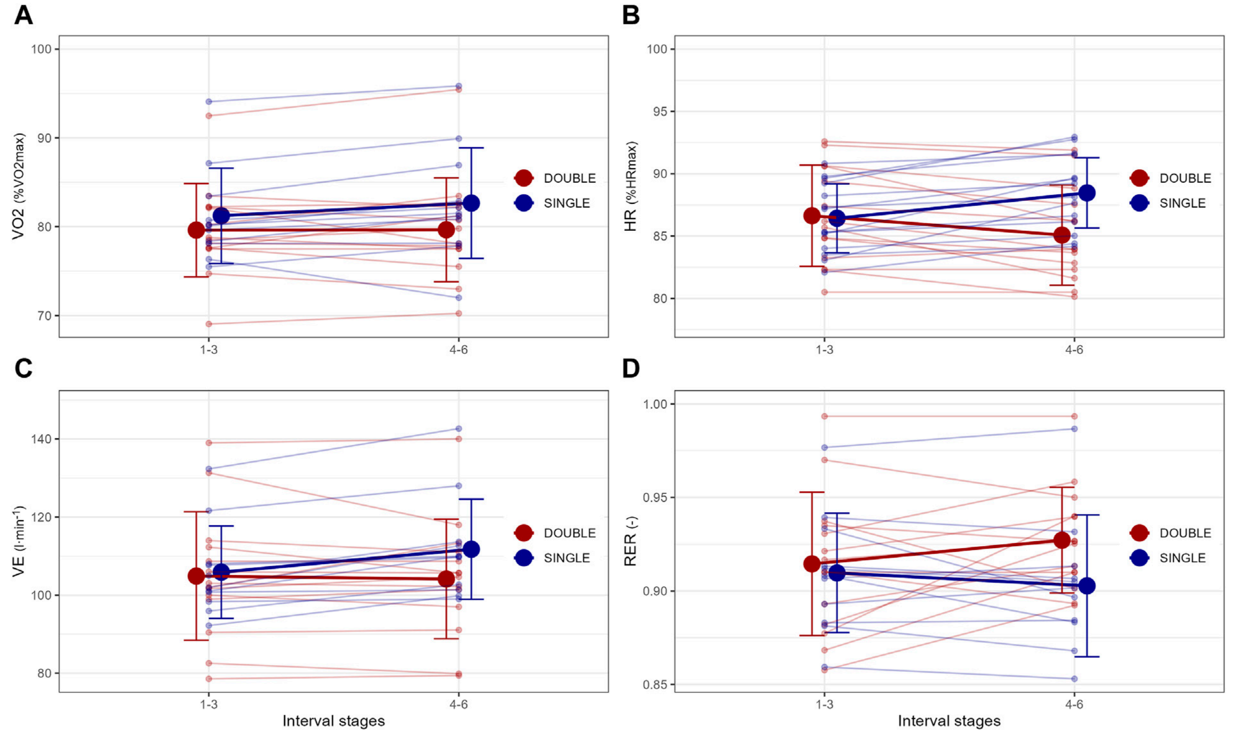

FIGURE 2
Acute responses in **(A)** oxygen uptake in percentage of maximal oxygen uptake (VO_{2max}), **(B)** heart rate in percentage of maximal heart rate (HR_{max}), **(C)** minute ventilation (VE), and **(D)** respiratory exchange ratio (RER) to different organization of time- and intensity-matched moderate-intensity training in fourteen male endurance athletes.

performing one long session was associated with overall higher physiological responses, attributed to a duration-dependent "drift" in HR, Bla, and RPE during the second compared to first part of the long session. Conversely, reductions in HR and Bla were observed in the second compared to first session during the performance of two short sessions. Additionally, performing one long session led to higher supine HR during a 60-min recovery period following sessions, as well as elevated session RPE and consequently training load, in comparison to two short sessions. Lastly, higher levels of perceived fatigue and muscle soreness were evident the following morning after the long session compared to the two short sessions.

Acute physiological responses

This study represents the first attempt to compare acute physiological responses between different methods of organizing moderate-intensity endurance training, specifically contrasting one long session with the increasingly popular "double-threshold training" approach, also by some, referred to as "the Norwegian method". As anticipated, engaging in one long session induced a duration-dependent "drift" in several internal intensity measures, resulting in significant overall higher acute physiological and perceptual responses compared to two shorter sessions. These significant physiological responses (e.g., HR and RPE) between one long and two shorter sessions were further strengthened by the large effect sizes revealed for most interval stages, implying practically relevant differences. The observed changes in the ratio between internal-to-external intensity measures during the long session are consistent with the recent concept of physiological "durability/resilience," characterized by the deterioration of physiological measures over time during prolonged endurance exercise (Maunder et al., 2021). While VO_2 and energy cost remained relatively stable both between and within the two training days, the increased HR during SINGLE likely stemmed from cardiovascular "drift," a well-recognized phenomenon in internal intensity measures during prolonged endurance exercise (Maunder et al., 2021; Smyth et al., 2022). This phenomenon is thought to be caused by decreased stroke volume and increased sympathetic nervous activity (Souissi et al., 2021). The observed increase in VE aligns with previous findings during prolonged endurance exercise, although in prior studies, this has been coupled with a "drift" in VO_2 and energy cost (Rønnestad et al., 2011; Hopker et al., 2017), which were not evident in the present study. This discrepancy may be attributed to the shorter duration and higher exercise intensity in our study compared to previous investigations of physiological "drift" during more prolonged low-intensity sessions (Rønnestad et al., 2011; Hopker et al., 2017). Moreover, Bla and BG concentrations increased from the first to second part of SINGLE, likely reflecting increased glycolytic energy turnover as the session progressed. These findings are consistent with previous studies of physiological responses to prolonged low-intensity training and are likely attributable to increased recruitment of fast-twitch muscle fibers (Rønnestad et al., 2011; Hopker et al., 2017). Moreover, the observed increase in RPE from the first to

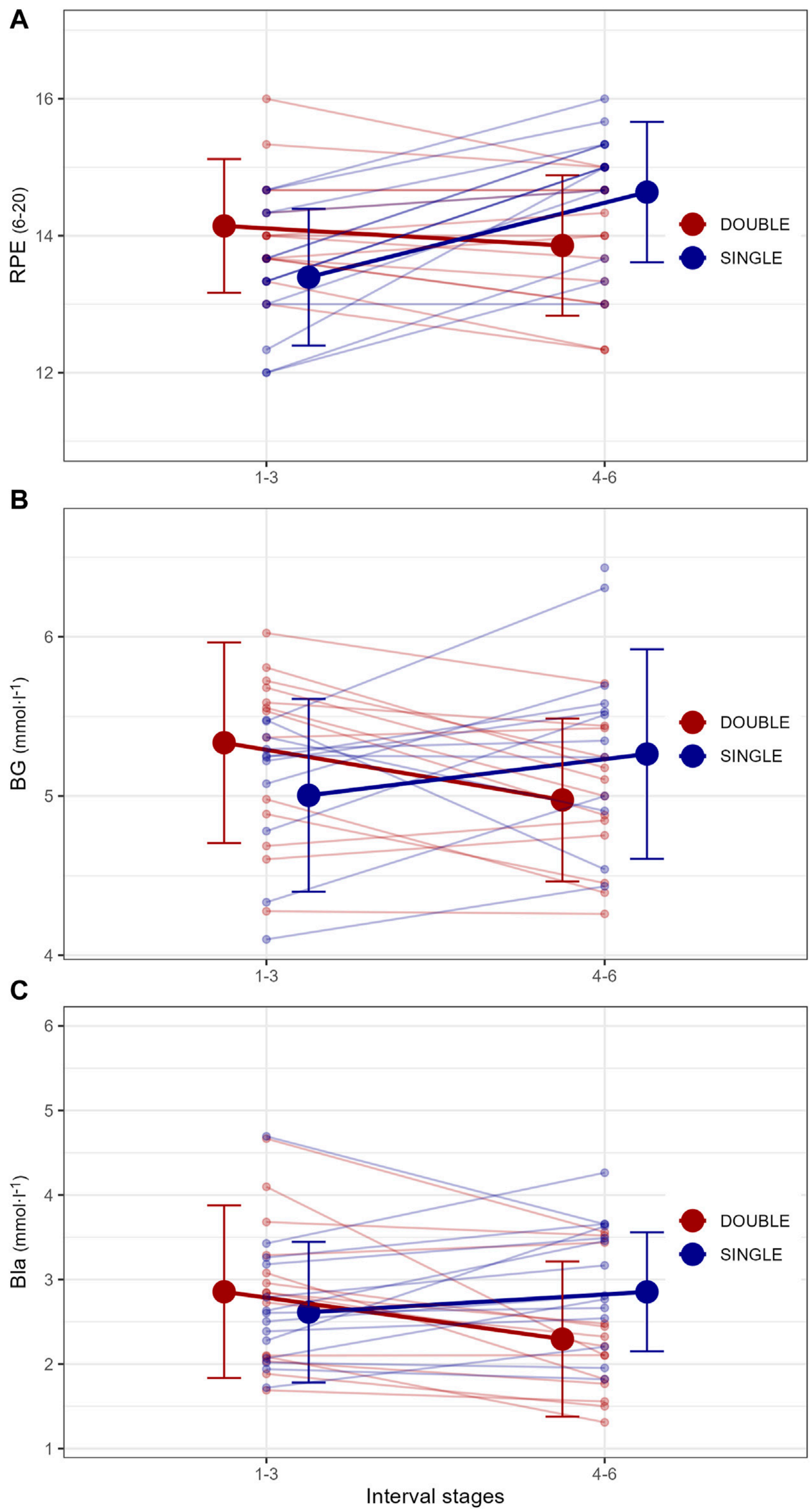

FIGURE 3
Acute responses in **(A)** rating of perceived exertion (RPE), **(B)** blood glucose concentrations (BG), and **(C)** blood lactate concentrations (Bla) to different organization of time- and intensity-matched moderate-intensity training in fourteen male endurance athletes.

second part of SINGLE aligns with previous studies investigating low-intensity training sessions (Rønnestad et al., 2011; Hopker et al., 2017; Talsnes et al., 2022), indicating an elevated perception of effort while maintaining the same external intensity over time.

The observed reduction in certain internal intensity measures (i.e., HR, Bla, and BG) from the first to second session of DOUBLE was notable. Specifically, we found significant interaction effects, indicating markedly lower levels of these intensity measures in the

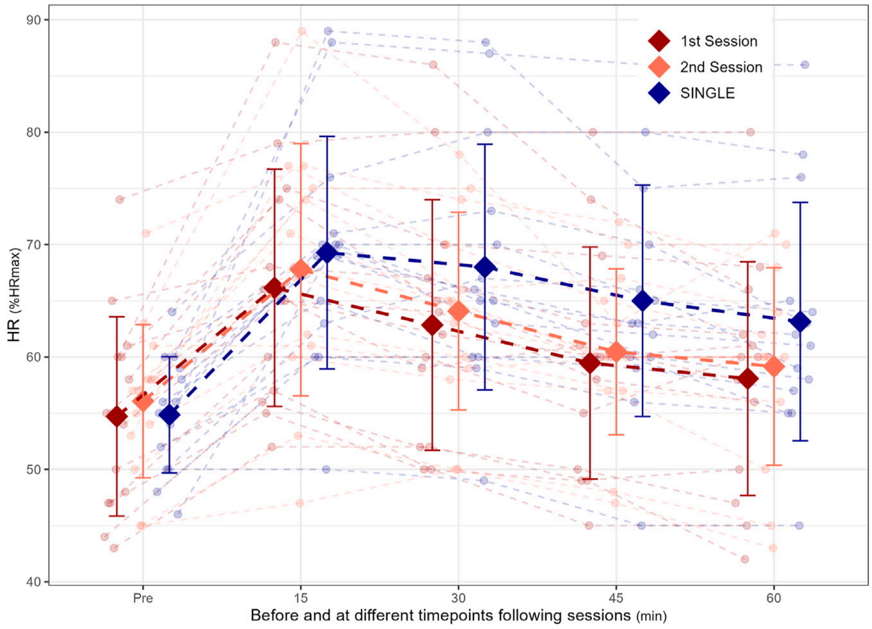

FIGURE 4
Supine heart rate (HR) before and at four time points following different organization of time- and intensity-matched moderate-intensity training in fourteen male endurance athletes.

second session of DOUBLE compared to the second part of SINGLE. These findings are consistent with a recent study examining acute physiological responses to different organizational approaches of low-intensity training in cross-country skiers (Talsnes et al., 2022). In that study, reduced HR and Bla responses were observed in the second session of low-intensity training performed on the same day. The mechanisms underlying the reduced HR response in the second session of DOUBLE in our study may involve circadian variations ("time-of-day effects") (Atkinson & Reilly, 1996; Chtourou & Souissi, 2012) and/or "preconditioning effects" from the first session (Kilduff et al., 2013). Additionally, the decreased Bla and BG levels from the first to second session of DOUBLE could be attributed to glycogen depletion and reduced CHO availability (Bartlett et al., 2015), despite the relatively short session duration and the provision of large amounts of exogenous CHO. However, these interpretations are not fully supported by the increased RER values observed in the second session of DOUBLE. Although the participants were instructed to replicate their dietary intake both the day before and the day constituting the experimental trial, no data on their nutritional intake or energy/CHO availability were included in the study. As such, the mechanisms driving the reduced physiological responses and particularly Bla and BG in the second session of DOUBLE remains speculative and should be investigated in future studies. Overall, these findings align with our hypotheses, suggesting a higher overall training stimulus when performing one long session compared to two shorter, time- and intensity-matched sessions of moderate-intensity training. Simultaneously, the lower physiological cost associated with the two shorter sessions indicates that this organization could allow for more accumulated time at this intensity in endurance athletes.

Autonomic recovery

Performing one long moderate-intensity training session was further associated with higher supine HR during the 60-min recovery period following sessions compared to two shorter sessions. This outcome aligns with the expected higher acute physiological responses observed with SINGLE. Although measures of heart rate variability (HRV) were not included in the present study, previous research has demonstrated that both HR and HRV following endurance exercise are affected by exercise intensity, duration, and training status, and may therefore serve as indicators of autonomic recovery following endurance exercise (Cottin et al., 2004; Seiler et al., 2007). Considering this, the current findings suggest that performing a time- and intensity-matched long session of moderate-intensity training induces greater training stress (i.e., autonomic disturbance) and potentially different recovery demands compared to two shorter sessions. Therefore, differences in signal-to-stress ratios between different organization of moderate-intensity training in endurance athletes should further be investigated using measures of both autonomic and hormonal (e.g., blood biomarkers) disturbance.

Measures of perceived training stress and recovery

Higher sRPE and internal training load (sRPE x duration) were evident in connection with SINGLE, indicating a higher perception of effort and most likely a higher overall training stimulus. This was further supported by increased levels of perceived fatigue and muscle soreness in the morning of the subsequent training day following SINGLE. These findings align with our hypotheses and

TABLE 3 Perceived training stress and recovery between two different organizations of time- and intensity-matched moderate-intensity training in fourteen male endurance athletes.

	SINGLE	DOUBLE		
	Total	First session	Second session	Total
Variables pre				
Motivation (1–10)	9.0 ± 2.0	9.0 ± 2.5	8.0 ± 1.8*	8.5 ± 2.3
Readiness (1–10)	7.5 ± 1.0	8.0 ± 1.0	7.5 ± 1.8	7.5 ± 1.0
Variables Post				
sRPE (1–10)	7.0 ± 1.0	6.0 ± 0.8	6.0 ± 1.3	6.0 ± 1.3#
sRPE load	929 ± 112	371 ± 47	371 ± 59	743 ± 98#
Physical training quality (1–10)	8.0 ± 1.5	8.0 ± 1.8	7.5 ± 1.0	7.8 ± 1.4
Technical training quality (1–10)	8.0 ± 1.8	7.0 ± 1.0	7.5 ± 1.8	7.5 ± 1.5
Mental training quality (1–10)	8.0 ± 1.0	8.0 ± 1.8	7.0 ± 2.5	7.5 ± 1.9
	SINGLE		DOUBLE	
Variables				
Sleep quality (1–10)	8.0 ± 1.0		7.5 ± 1.0	
General mental wellbeing (1–10)	8.0 ± 1.0		9.0 ± 1.0	
General physical wellbeing (1–10)	8.0 ± 1.7		8.0 ± 1.7	
Readiness to train (1–10)	7.0 ± 1.5		7.5 ± 1.0	
Muscle soreness (1–10)	6.0 ± 2.5		7.0 ± 2.5#	
Fatigue (1–10)	7.0 ± 2.5		8.0 ± 1.0#	
Attractiveness to the training day (1–10)	7.5 ± 1.0		8.0 ± 1.0	

SINGLE, one 6 × 10-min "threshold interval session"; DOUBLE, two 3 × 10-min "threshold interval sessions"; Pre, 15-min before sessions, Post, 15-min after sessions; sRPE, session rating of perceived exertion.
*Significant different from first session within DOUBLE ($p < 0.05$).
#Significant different from SINGLE ($p < 0.05$).

reflect the higher overall physiological responses induced by performing one long session. Although no differences were found between SINGLE and DOUBLE in reported training quality (i.e., physical, technical, mental perspectives), lower motivation was reported before the second compared to first session of DOUBLE. This finding might be related to the participants' lack of familiarity with performing "double-threshold training" and the laboratory-based nature of the design, which may differ from how this method would be implemented in a more ecologically valid setting.

Practical applications and future research

Although we achieved high internal validity of the study protocol by employing a time- and intensity-matched laboratory design as a starting point, it differs somewhat from the actual use of the method in sports practice. One reported benefit of "double-threshold training" is to increase the overall volume of moderate-intensity training. Therefore, a logical next step would be to increase the duration of the two short sessions to achieve the same internal training load as one single session. In our case, an additional 10-min duration with the same sRPE for the two short sessions would be necessary to match the internal training load of the single session. Alternatively, two shorter sessions at the same internal intensity as one long session could be performed at a higher external intensity (i.e., more competition-relevant speed or power), thereby enhancing motor unit recruitment. Moreover, the ability to switch between exercise modes in sports that utilize different modes (e.g., triathlon and cross-country skiing) could further enhance the tolerance of moderate-intensity training due to variations or reductions in muscular and mechanical loading between sessions. Lastly, performing one longer session leads to a higher acute physiological response due to a duration-dependent "drift" in physiological measures, which may elicit a greater magnitude of molecular signaling (i.e., training stimulus) and influence subsequent adaptations differently.

Conclusion

One long moderate-intensity training session was associated with a duration-dependent "drift" in acute physiological responses compared to two short time- and intensity-matched sessions. Simultaneously, the lower cost of the two shorter sessions indicates that such organization could allow for more accumulated time at this intensity. While future training intervention studies are required to investigate actual training effects, these findings serve as a starting point to better understand the pros and cons (i.e., different signal-to-stress ratios) of organizing moderate-intensity training as one long versus shorter sessions more frequently (e.g., as "double threshold training") in endurance athletes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethical approval was not required for the studies involving humans because the Regional Committee for Medical and Health Research Ethics waives the requirement for ethical approval for such studies. Therefore, the study was done in accordance with the institutional requirements and in line with the Helsinki declaration. Approval for data security and handling was obtained from the Norwegian Centre for Research Data. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RK: Conceptualization, Investigation, Writing–original draft, Writing–review and editing. P-ØT: Conceptualization, Investigation, Writing–review and editing. KS: Formal Analysis, Visualization, Writing–review and editing. ØS: Conceptualization, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Blood flow restriction combined with resistance training on muscle strength and thickness improvement in young adults: a systematic review, meta-analysis, and meta-regression

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Background: High-intensity resistance training is known to be the most effective method for enhancing muscle strength and thickness, but it carries potential injury risks. Blood flow restriction (BFR) combined with resistance training has been proposed as a safer alternative method for improving muscle strength and thickness.

Methods: A meta-analysis was conducted, including 20 studies from five databases that met the inclusion criteria, to assess the efficacy of BFR combined with resistance training compared to traditional resistance training (NOBFR). The analysis focused on changes in muscle strength and thickness. Subgroup analysis and meta-regression were performed to explore the effects of tourniquet width and pressure.

Results: The findings showed that BFR combined with resistance training is comparable to traditional resistance training in enhancing muscle strength [0.11, 95%CI: (−0.08 to 0.29), I^2 = 0%] and muscle thickness [−0.07, 95% CI: (−0.25 to 0.12), I^2 = 0%]. Subgroup analysis indicated no significant differences in muscle strength (P = 0.66) and thickness (P = 0.87) between low-intensity BFR training and other intensity levels. Meta-regression suggested that tourniquet width and pressure might affect intervention outcomes, although the effects were not statistically significant (P > 0.05).

Conclusion: BFR combined with resistance training offers a viable alternative to high-intensity resistance training with reduced injury risks. We recommend interventions of 2-3 sessions per week at 20%–40% of 1 RM, using a wider cuff and applying an arterial occlusion pressure of 50%–80% to potentially enhance muscle strength and thickness. It is also recommended to release tourniquet pressure during rest intervals to alleviate discomfort. This protocol effectively improves muscle strength with minimal cardiac workload and reduced risk of adverse events.

Systematic Review Registration: [https://www.crd.york.ac.uk/prospero/display_record.php?ID=CRD42023495465], identifier [CRD42023495465].

KEYWORDS

resistance training (RT), muscle strength, muscle thickness, blood flow restriction (BFR), young adults

1 Introduction

Muscle, as a major component of the locomotor system, muscle mass determines the athletic capability and sports performance (van der Zwaard et al., 2021; Khare et al., 2023). Muscle mass is critical for both athletes and chronically ill people. For athletes, muscle mass determines performance to influence competitive results. For chronically ill or elderly populations, muscle mass correlates with longevity (Cruz-Jentoft and Sayer, 2019; Fabero-Garrido et al., 2022a; Alizadeh Pahlavani, 2022). Traditional resistance training has been validated as an effective non-pharmacological intervention for enhancing muscle mass and strength (Fragala et al., 2019). High-intensity (HI) resistance training has demonstrated superior effect on muscle strength and thickness improvement compared to moderate-to low-intensity (LI) resistance training (Csapo and Alegre, 2016). However, it is imperative to note that HI resistance training may induce pain and injuries to populations with chronic disease, such as hypertension or osteoarthritis (Wang et al., 2022a; Wang et al., 2022b). Consequently, it is crucial to explore alternative approaches that yield benefits akin to HI resistance training while mitigating associated risks.

Recent studies have revealed that LI resistance training, when combined with blood flow restriction (BFR), triggers heightened metabolic stress, thereby modulating signal transduction in musculoskeletal cells and achieving muscle strength and thickness improvements comparable to those achieved through HI resistance training (Krzysztofik et al., 2019; Koc et al., 2022; Krzysztofik et al., 2022). BFR is an intervention method that involves the application of restrictive equipment to reduce blood flow in the proximal segment of the limb (Lorenz et al., 2021). This intervention indirectly influences cellular metabolism by accumulating metabolites and simulates a localized hypoxic environment during the reduction of blood flow in the proximal limb segment (Krzysztofik et al., 2019; Lorenz et al., 2021). The combination of BFR with resistance exercise has been implemented across diverse populations in both clinical and non-clinical setting (Krzysztofik et al., 2019; Krzysztofik et al., 2022; Colapietro et al., 2023). Consequently, BFR coupled with LI resistance training emerges as a safe alternative treatment, presenting a viable option to traditional resistance training protocols for enhancing muscle and physical functions among patients in the clinical setting or sedentary populations.

Despite the growing utilization of BFR in combination with resistance training in various studies and clinical settings, there remains a conspicuous absence of standardized criteria regarding training protocols and BFR equipment among participants. Key parameters such as occlusion pressure, cuff width, and the choice of resistance level are pivotal in determining the effectiveness of BFR interventions. Variations in treatment protocols, including occlusion pressure [often recommended to be between 50%–80% of arterial occlusion pressure (Li et al., 2023)], cut width, the number of sets and repetitions performed, total training sessions, and duration, may contribute to differences in the treatment's efficacy within clinical applications (Brumitt et al., 2021a). Moreover, a dearth of evidence exists to comprehensively evaluate the impact of BFR combined with resistance training at various intensity levels on improving muscle strength and thickness. This study employs meta-regression analysis to evaluate the impact of these parameters on muscle strength and thickness improvement, aiming to provide a clearer understanding of how different training and equipment characteristics affect outcomes. The influence of training and equipment characteristics on muscle function improvement remains a crucial area requiring further exploration and in-depth discussion.

This study aims to address these gaps by examining the influence of treatment characteristics on muscle strength and thickness improvement through a systematic review and meta-analysis. A subsequent meta-regression analysis intends to rigorously investigate the association between specific protocol details and muscular improvement. The insights gleaned from this study not only contribute to the current understanding of resistance training with BFR but also furnish valuable information for designing effective and targeted treatment programs.

2 Method

This review was prospectively registered with PROSPERO (ref. CRD42023495465) and was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher et al., 2009) and the Cochrane Handbook (JPT et al., 2024).

The screening of studies, quality assessment, and data extraction were independently conducted by two researchers, FM and JH. Any discrepancies in assessments were resolved through discussion. In instances where a consensus could not be reached, a third researcher, YW, was consulted to facilitate an agreement.

2.1 Data sources and study selection

The search was initiated on 8 October 2023, using multiple databases including PubMed, Web of Science, EBSCO, Embase, and the Cochrane Library. The search involved keywords such as "*Blood Flow Restriction,*" "*hypoxia,*" and "*resistance training,*" and was limited to studies published between 1985 and 2023. The detailed search strategies for each database are summarized in Table 1.

An example of the study search strategy and the results obtained using the PubMed database is provided in Supplementary Appendix Table S1.

Prior to commencing the screening process, studies were included if they met the following criteria: 1) participants were healthy adults aged 18+ years; 2) the intervention involved resistance training combined with BFR; 3) the intervention of control group received usual care without BFR (NOBFR); 4) the study outcomes centered on muscle thickness (cross-sectional area (CSA) or girth) and muscle strength (1 repetition maximum (RM) or maximal voluntary torque (MVT)); 5) the studies were randomized controlled trials; 6) the studies were available in English.

Studies were exclued, if: 1) participants had chronic diseases or pain, such as hypertension; 2) the intervention was acute exercise and aerobic training with BFR; 3) the studies were observational or cohort trails, conference reports, and review articles; 4) the studies were published in a language other than English.

The searched studies were evaluated against these criteria in two phases: 1) assessment of each study's abstract and title and 2)

TABLE 1 Database search strategies.

Database	Search Strategy
PubMed	("Resistance Training" [MeSH Terms] OR "strength training" [Title/Abstract] OR "resistance exercise" [Title/Abstract] OR "weight training" [Title/Abstract]) AND ("Hypoxia" [MeSH Terms] OR "altitude" [Title/Abstract] OR "hypoxic training" [Title/Abstract] OR "hypoxic exposure" [Title/Abstract]) AND ("Blood Flow Restriction Therapy" [MeSH Terms] OR "karats" [Title/Abstract] OR "occlusion training" [Title/Abstract] OR "blood flow restriction" [Title/Abstract] OR "br training" [Title/Abstract] OR "br exercise" [Title/Abstract])
Web of Science	TS=("Resistance Training" OR "strength training" OR "resistance exercise" OR "weight training") AND TS=("Hypoxia" OR "altitude" OR "hypoxic training" OR "hypoxic exposure") AND TS=("Blood Flow Restriction Therapy" OR "karats" OR "occlusion training" OR "blood flow restriction" OR "br training" OR "br exercise")
EBSCO	("Resistance Training" OR "strength training" OR "resistance exercise" OR "weight training") AND ("Hypoxia" OR "altitude" OR "hypoxic training" OR "hypoxic exposure") AND ("Blood Flow Restriction Therapy" OR "karats" OR "occlusion training" OR "blood flow restriction" OR "br training" OR "br exercise")
Embase	('Resistance Training'/exp OR 'strength training' OR 'resistance exercise' OR 'weight training') AND ('Hypoxia'/exp OR 'altitude' OR 'hypoxic training' OR 'hypoxic exposure') AND ('Blood Flow Restriction Therapy'/exp OR 'karats' OR 'occlusion training' OR 'blood flow restriction' OR 'br training' OR 'br exercise')
Cochrane Library	("Resistance Training" OR "strength training" OR "resistance exercise" OR "weight training") AND ("Hypoxia" OR "altitude" OR "hypoxic training" OR "hypoxic exposure") AND ("Blood Flow Restriction Therapy" OR "karats" OR "occlusion training" OR "blood flow restriction" OR "br training" OR "br exercise")

evaluation of the full text of potentially relevant studies. The search and screening process was documented using the PRISMA flow diagram (Page et al., 2021). The researchers used Endnote software for the screening process.

2.2 Quality assessment and data extraction

2.2.1 Assessment of bias

The methodological quality of the included studies underwent rigorous assessment by the researchers using two tools: the Cochrane Risk of Bias 2 (RoB 2) tool (Higgins et al., 2011) and the PEDro (Physiotherapy Evidence Database) scale (Maher et al., 2003). Each tool's guidelines were followed during the assessment process, evaluating five key domains: the randomization process, confounding factors, sample selection, missing data, and measurement of outcomes. Utilizing the Cochrane RoB 2 tool, the risk was classified as "low," "some concerns," or "high," providing a detailed overview of the methodological quality of the included studies. Additionally, the 11-item PEDro scale (http://www.pedro.fhs.usyd.edu.au) was employed to gauge methodological quality (de Morton, 2009), with items scored as either present ("1") or non-present ("0"), allowing for a comprehensive assessment of each study. The methodological quality was categorized as "low" (total score less than 4), "some concerns," and "high" (total score greater than 8). The evaluation results are detailed in Figure 2; Table 1. This rigorous approach ensures the reliability and validity of the meta-analysis findings.

2.2.2 Data extraction and synthesis

Data extracted from each included study were divided into two categories: participant characteristics and trial characteristics. Participant characteristics encompassed crucial information such as sample age, body weight, BMI, and sample size. It is noted that several studies included multiple intervention groups and self-control groups. To prevent duplication of samples, the sample size of self-control studies was averaged equally. For studies with different intervention groups, each intervention was reported separately, and the control group's sample size was also equally distributed. Trail characteristics encompassed training intensity, tourniquet width, occlusion pressure, tourniquet application time, training volume, rest duration between sets, training duration, frequency, and the specific outcomes obtained in each study. Continuous numerical data were extracted using mean and standard deviation (SD). Further details regarding the extracted data are showed in Table 2. Investigation into the effect of trial characteristics of BFR intervention on muscle strength and thickness improvement necessitated the transformation of certain trail characteristics into binary variables for data analysis. Specifically, the training intensity with BFR was dichotomized into "Low-intensity with BFR" (50% 1 RM) or "Other intensity with BFR" [including middle-(50–69% 1RM) and high-intensity with BFR (70–84% 1RM)]. The inflation of the tourniquet during exercise interventions was categorized as either "Inflated for the entire exercise protocol" or "Inflated during exercise and deflated during rest periods."

For the meta-analysis and meta-regression analysis, this study utilized the mean and SD of the post-intervention test results for each study's intervention and control groups. The outcomes measured included including muscle CSA and girth, as well as muscle strength (including 1 RM and MVT). Notably, the meta-analysis was conducted separately for muscle thickness and muscle strength.

2.3 Data analysis

The initial meta-analysis of the extracted data took into consideration the methodological heterogeneity arising from diverse muscle measurement and testing methods. To address this, a standardized mean difference (SMD) (Bakbergenuly et al., 2020) was employed for data analysis. This approach utilizes statistical units to standardize various clinical units, effectively reducing discrepancies caused by differing testing

TABLE 2 Study quality assessment using the PEDro scale.

Study	1	2	3	4	5	6	7	8	9	10	11	Overall	Quality
Barcelos et al. (2015)	1	1	1	1	0	0	0	1	1	1	1	8/11	High
Biazon et al. (2019)	1	1	1	1	0	0	0	1	1	1	1	8/11	High
Bradley et al. (2022)	1	1	1	1	0	0	1	0	1	1	1	8/11	High
Brumitt et al. (2021c)	1	1	1	1	0	0	1	1	1	1	1	9/11	High
Centner et al. (1985)	1	1	1	1	0	0	1	1	1	1	1	9/11	High
Cook and Cleary (2019)	0	1	1	1	0	0	0	1	1	1	1	7/11	Some concern
Colapietro (2023)	1	1	1	1	0	0	0	1	1	1	1	8/11	High
Fahs et al. (2015)	1	1	1	1	0	0	0	0	1	1	1	7/11	Some concern
Fernandes et al. (2020)	1	1	1	1	0	0	0	1	1	1	1	8/11	High
Hackney et al. (2016)	1	0	1	1	0	0	0	1	1	1	1	7/11	Some concern
Kacin and Strazar (2011)	1	0	1	1	0	0	0	1	1	1	1	7/11	Some concern
Laurentino et al. (2008)	1	0	1	1	0	0	0	1	1	1	1	7/11	Some concern
Laurentino et al. (2022)	1	1	1	1	0	0	0	1	1	1	1	8/11	High
Lixandrão et al. (2015)	1	0	1	1	0	0	0	0	1	1	1	6/11	Some concern
Madarame et al. (2008)	0	1	1	1	0	0	0	1	1	1	1	7/11	Some concern
Ozaki et al. (2013)	1	1	1	1	0	0	0	1	1	1	1	8/11	High
Reece et al. (1985)	1	1	1	1	0	0	0	1	1	1	1	8/11	High
Teixeira et al. (2022)	1	1	1	1	0	0	0	0	1	1	1	7/11	Some concern
Vechin et al. (2015)	1	0	1	1	0	0	0	1	1	1	1	7/11	Some concern
Yasuda et al. (2014)	1	1	1	1	0	0	0	1	1	1	1	8/11	High

methods and clinical units (Andrade, 2020). The SMD calculation is the following:

$$SMD = (Mean_{BFR} - Mean_{Non-BFR}) \div SD_{BFR}$$

Following this, the present study evaluated the heterogeneity of the included studies' results using Cochran's Q statistic (Schulzke and Patole, 2021), a well-established tool for accurately gauging statistical heterogeneity, alongside Higgins and Thompson's I^2 statistic to quantify the heterogeneity level (Bowden et al., 2011). Meanwhile, forest plots were used for visually representation of the analysis results. The I^2 statistic was used to quantify the degree of heterogeneity across studies, with values of 25%, 50%, and 75% denoting low, moderate, and high heterogeneity (Higgins et al., 2003), respectively. In instances where the I^2 value exceeded 75%, indicating significant inconsistency among these studies, a reassessment was conducted using a random-effects model. After that, publication bias and sensitivity analyses were performed to comprehend the reasons behind the observed heterogeneity. Specifically, to evaluate the potential for publication bias, a meta-bias assessment was conducted in the study. A funnel plot was constructed and the Egger's test was used to detect statistically significant publication bias ($P < 0.1$) (JPT et al., 2024). Furthermore, a sensitivity analysis was executed to explore the impact of each study on bias. Studies demonstrating high inconsistency were considered for potential exclusion in the final analysis. Researchers assigned weights to each included study, where studies with high inconsistency were weighted as 0 while others were weighted as 1 for the formal analysis.

2.4 Meta-regression analysis

This study conducted a meta-regression analysis to delve into the relationship between trial characteristics and the improvement of muscle strength and thickness. Meta-regression enables the exploration of potential sources of heterogeneity by quantifying the impact of various factors on intervention effects. The Knapp-Hartung modification was incorporated to bolster the robustness of the analysis. The primary objective of this analysis was to discern significant associations between individual trial characteristics and the outcomes, thereby offering valuable insights into the factors influencing muscle response across the included studies.

2.5 Statistical analysis

This study employed a combination of software tools to execute various aspects of the data analysis process. Endnote (Clarivate, Philadelphia, United States) was utilized for reference management and the screening process. The methodological quality assessment of

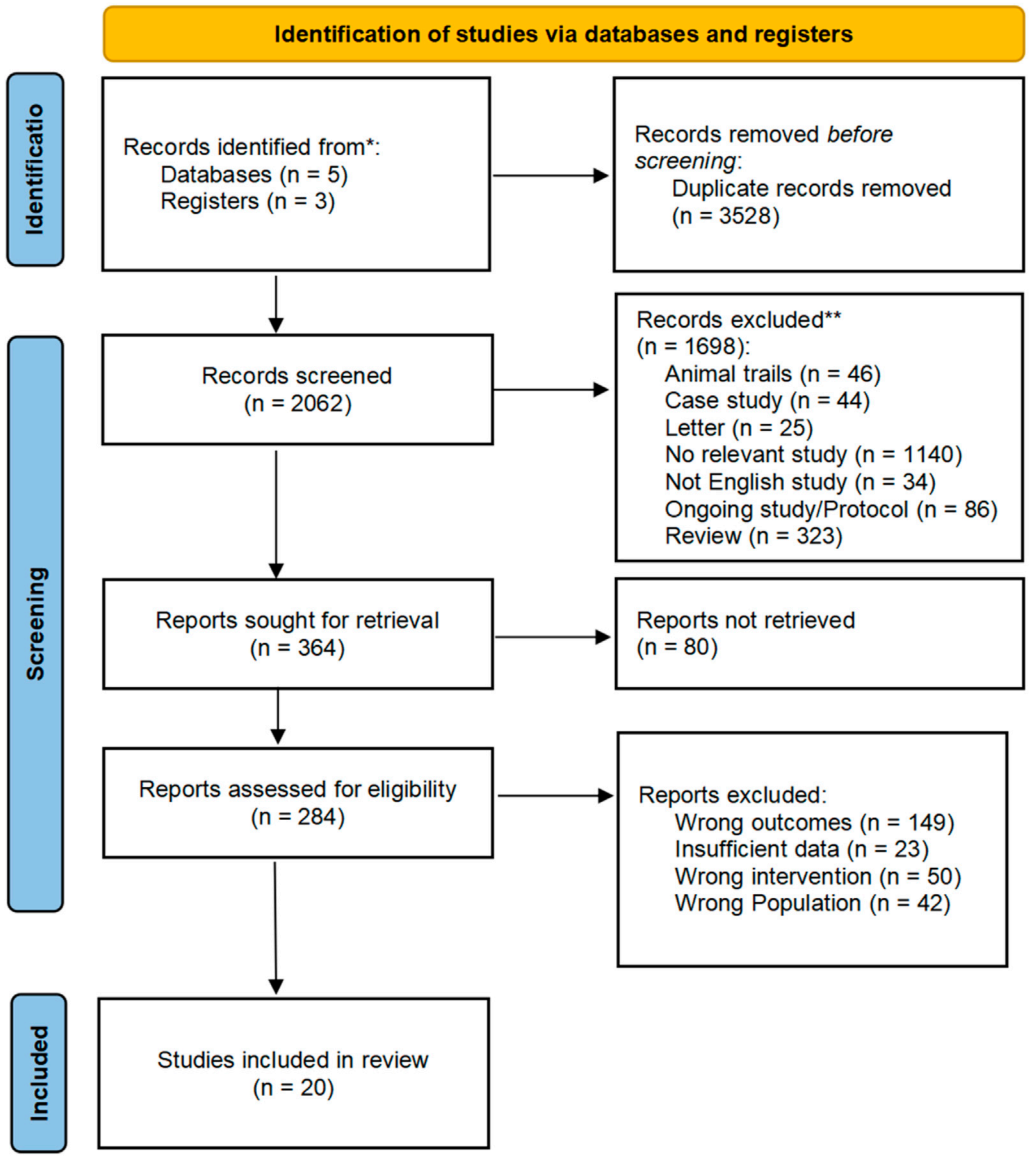

FIGURE 1
The PRISMA flow diagram of studies selection process.

the included studies was conducted using Excel to implement RoB 2, and the *Robvis* package (McGuinness and Higgins, 2020) in R Studio (R version 4.2.3; RStudio, PBC, Boston, MA, United States) was adopted for visualizing the RoB assessment. The results were exhibited in two figures: a summary of five domains and a traffic light figure displaying each study's risk. R studio served as the primary tool for conducting the meta-analysis, publication bias analysis, sensitivity analysis, and figure generation. Stata 18 (StataCorp, College Station, TX, United States) was utilized specifically for the meta-regression analysis to explore the relationships between moderators and outcomes. All results were calculated with 95% confidence intervals (CI). For the determination of statistical significance in BFR intervention effects, the threshold was set at $P < 0.05$. In addition, statistical significance for heterogeneity was defined as $P < 0.1$ or $I^2 > 75\%$, and that for publication bias was defined as $P < 0.1$.

3 Results

3.1 Search results

The study identified 20 randomized controlled trails that met the specified inclusion criteria. Comprehensive searches using keywords across five databases yielded a total of 5,590 literature records. Following a careful screening process, 3,528 duplicate studies were removed, employing both automated and manual procedures facilitated by Endnote. Following this, three researchers conducted an initial screening of the included studies based on the predetermined criteria, assessing the title and abstract of each literature record. Among these, 80 records were excluded due to incomplete reporting of the study, and 284 records were screened in full text. During the full-text assessment, 23 articles were excluded due to insufficient content, as they only included change

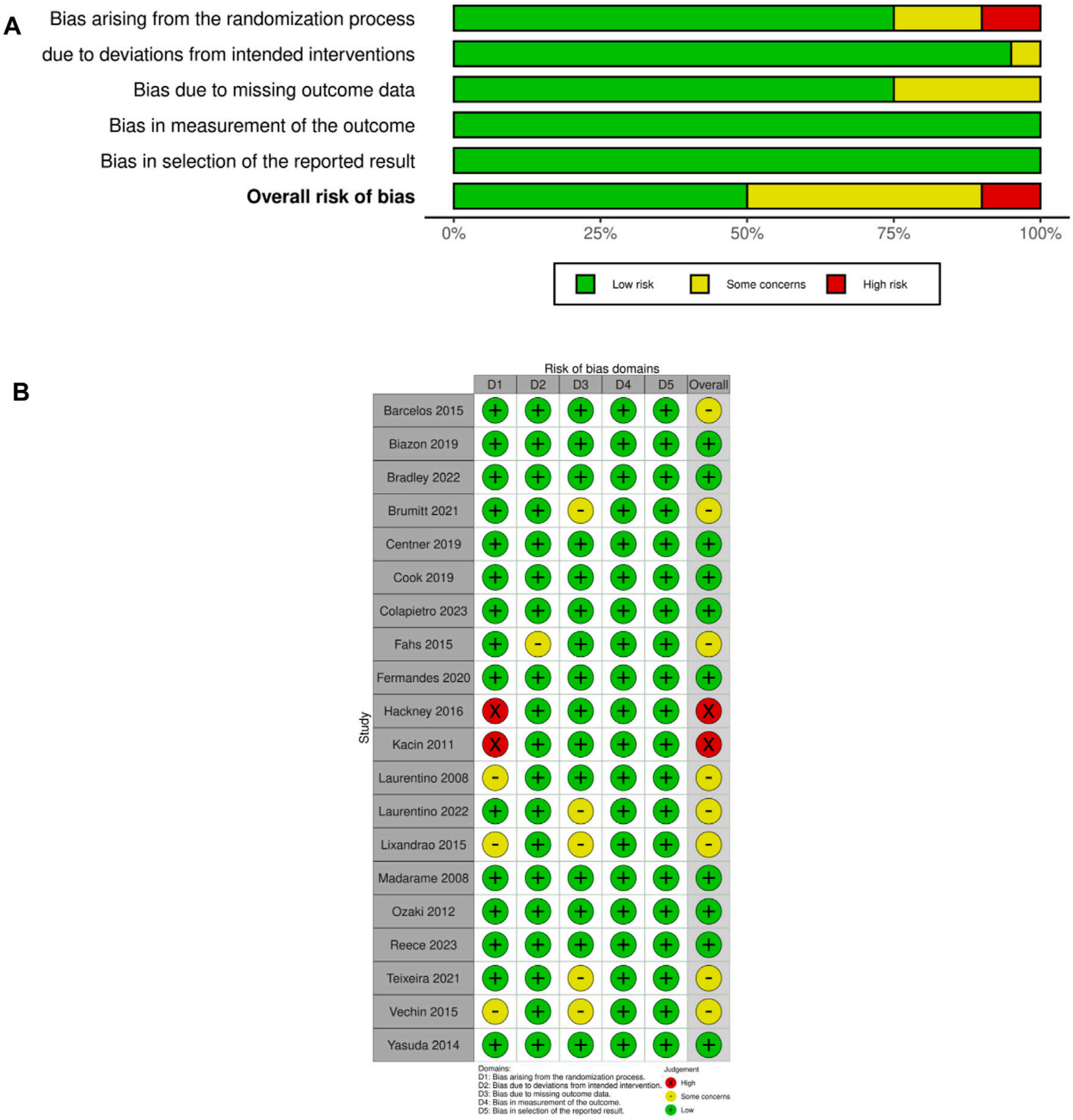

FIGURE 2
(A) RoB 2 summary plot; **(B)** RoB 2 traffic light figure. Note: The figures were produced using R packages (McGuinness and Higgins, 2020).

data between pre-training and post-training without detailed experimental results. Additionally, 50 studies were excluded due to inappropriate intervention for this review, such as BFR combined with aerobic training or walking trials, and 42 trials were excluded due to inappropriate participants, such as pre- and post-knee surgery patients. The detailed screening process is illustrated in Figure 1.

3.2 Risk assessment for study quality

The methodological quality of the included studies has been meticulously assessed and is presented in Figure 2; Table 2. According to the RoB 2 assessment, ten studies (50%) were determined to exhibit a low risk of bias in their methodology, while only two studies (10%) were deemed to have a high risk. The remaining studies were found to have some concerns regarding their methodological quality. In addition, the PEDro scale scores of the included studies ranged from 6 to 9, with an average score of 7.6 ± 0.75. This range indicated a predominantly high methodological quality across the selected studies. Specifically, nine studies (45%) exhibited some concerns with their methodological quality, while five studies (25%) failed to employ random allocation groups. It is noteworthy that only one study (Lixandrão et al., 2015) scored 6 points and was assessed as having some concerns at RoB 2. This particular study might have contributed to the observed heterogeneity and potentially influenced the overall robustness of the outcomes.

TABLE 3 Summary of participant characteristics and trial characteristics of included studies.

Study	Participant characteristics				Trial characteristics								
	Age (yr)	Body weight (kg)	BMI [kg·m]	Sample Size	Intervention	Tourniquet (width * length, cm)	The occlusion pressure	Tourniquet application time	Training protocol	Rest	Duration (weeks)	Frequency (per week)	Outcomes
Barcelos et al. (2015)	21 ± 4.76		23.3 ± 3.39	10	50% 1-RM	10 * 80	200 mmHg	Inflated for the entire exercise protocol	76	1 min between set	8	2	The cross-sectional area (CSA) of the quadriceps 1RM
	22 ± 2.9		22.4 ± 4.44	10	20% 1-RM	10 * 80	200 mmHg		25				
	21 ± 3.23		25.0 ± 6.05	10	20% 1-RM	10 * 80	200 mmHg		42				
Biazon et al. (2019)	22 ± 3	72.7 ± 10.7	22.81 ± 2.99	10	80% 1-RM	NA	NA	-	3 * 10	1 min between set	10	2	Unilateral quadriceps maximum dynamic strength; vastus lateralis (VL) muscle CSA; echo intensity; pennation angle (PA)
				10	80% 1-RM	17.5 * 92	60% of occlusion pressure (81.85 ± 4.45 mmHg)	Inflated during the exercise and deflated during the rest periods	3 * 10				
				10	20% 1-RM				3 * 20				
Bradley et al. (2022)	28.8 ± 6.3	67.0 ± 8.4		10	80% 1-RM(Rowing) 60% 1-RM(Deadlift)	-	-	-	Rowing: 3 * 1 min Deadlift: 20/10/10/10	0.5 min between set; 3 min between exercise	4	2	VL and biceps femoris (BF) CSA; 1-RM of deadlift; Thigh circumference; maximal aerobic capacity (VO2max)
	29.2 ± 8.0	80.4 ± 22.6		10	40% 1-RM(Rowing) 30% 1-RM(Deadlift)	11.43 * 86.36	-	Inflated for the entire deadlift protocol	Rowing: 3 * 1 min Deadlift:10/5/5/5				
Brumitt et al. (2021c)	25.8 ± 1.6			17	30% 1RM	-	-	-	30/15/15/15 (the single-leg knee extension exercise) 30/15/15/15 (the standing single-leg hamstring curl)	0.5 min between set	8	2	supraspinatus, shoulder ER, quadriceps, and hamstrings strength quadriceps CSA.
					30% 1RM	-	80% LOP	Inflated for the entire lower extremities protocol					
Centner et al. (1985)	26.1 ± 4.2	76.4 ± 15.4	23.5 ± 3.5	14	70%–85% 1RM	-	-	-	3 * 6–12	1 min between set; 3 min between exercise	14	3	CSA; Unilateral isometric maximum voluntary contraction (MVC); Achilles Tendon Properties;
	27.1 ± 4.7	85.0 ± 9.3	26.3 ± 3.5	11	20%–35% 2RM	12	50% AOP	Inflated during the exercise and deflated during the rest periods	30/15/15/15				

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TABLE 3 (*Continued*) Summary of participant characteristics and trial characteristics of included studies.

Study	Participant characteristics				Trial characteristics								
	Age (yr)	Body weight (kg)	BMI [kg·m]	Sample Size	Intervention	Tourniquet (width * length, cm)	The occlusion pressure	Tourniquet application time	Training protocol	Rest	Duration (weeks)	Frequency (per week)	Outcomes
													Lifestyle Parameters
Cook and Cleary (2019)	76.3 ± 8.7	73.3 ± 10.9	26.5 ± 3.0	11	70% 1RM	-	-	-	Volitional failure (HL-Knee extension 23.5 ± 5.0)	1 min between set; 3 min between exercise	12	2	CSA; Strength (Unilateral, isometric maximum voluntary contraction (MVC))
	76.4 ± 6.6	75.4 ± 10.9	27.5 ± 3.3	10	30% 1RM	6 * 83	66% of predicted arterial occlusion pressure	Inflated during the exercise and deflated during the rest periods	Volitional failure (BFR-Knee flexion 18.1 ± 8.3)				
Colapietro (2023)	22.9 ± 3.78	70.1 ± 7.72	24.7 ± 1.82	10	50%–80% 1RM	-	-	-	3 * 8	0.5 min rest between sets; 1 min rest between exercises	4	3	Eccentric knee flexor peak moment; Rate of perceived exertion (RPE); CSA.
	20.7 ± 2.36	68.6 ± 7.23	24.3 ± 1.54	10	10%–30% 1RM	11.43 * 86.36	80% LOP	Inflated during the exercise and deflated during the rest periods	30/15/15/15	0.5 min rest between sets; 2 min rest between exercises			
Fahs et al. (2015)	55 ± 7	82.7 ± 16.5	26.7 ± 4.7	17	30% 1RM	-	-	-	Volitional failure (45 ± 15 repetitions)	NA	6	3	Muscle thickness (MTh); muscle strength (1 RM); Thigh circumference
					30% 1RM	5	80% of AOP but no higher than 240 mmHg	Inflated for the entire exercise protocol	Volitional failure (44 ± 13 repetitions)				
Fernandes et al. (2020)	20.2 ± 1.1	62.3 ± 6.9	23.3 ± 2.7	14	65%–85% 1RM	-	-	-	3 * 8–12	0.5 min rest between sets	4	3	Circumference; hand pressure strength
	20.1 ± 1.6	60.6 ± 8.6	23.1 ± 3.6	14	30%–55% 1RM	7 * 80	160 mmHg	Inflated for the entire exercise protocol	3 * 15–25				
Hackney et al. (2016)	33.8 ± 13.8	70.2 ± 17.0	70.2 ± 17.0	6	70%–80% 1RM	-	-	-	Volitional failure (3 * nr)	1.5 min rest between exercises	3.5 (25 days)	3	CSA; 1RM.
	30.1 ± 12.1	66.7 ± 6.7	66.7 ± 6.7	7	20%–30% 1RM	6 * 83	140 ± 10 mmHg	Inflated for the entire exercise protocol					

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TABLE 3 (*Continued*) Summary of participant characteristics and trial characteristics of included studies.

Study	Participant characteristics				Trial characteristics								
	Age (yr)	Body weight (kg)	BMI [kg·m]	Sample Size	Intervention	Tourniquet (width * length, cm)	The occlusion pressure	Tourniquet application time	Training protocol	Rest	Duration (weeks)	Frequency (per week)	Outcomes
Kacin and Strazar (2011)	22.5 ± 0.6	76.7 ± 3.1		10	15% MVC force	-	-	-	Volitional failure (4 * nr)	2 min between set.	4	4	Muscle CSA; MVC force; EMG; Muscle oxygen; Arterial blood pressureHR.
						13 * 30	230 mmHg	Inflated during the exercise and deflated during the rest periods	Volitional failure (4 * 22–36 repetitions)				
Laurentino et al. (2008)	23.55 ± 3.37	71.44 ± 11.05		8	80% 1RM	-	-	-	3–5 sets	2 min between set.	8	2	CSA; 1RM.
					80% 1RM	14 * 90	125.6 ± 15.0	Inflated during the exercise and deflated during the rest periods					
	22.42 ± 3.41	80.15 ± 11.758		8	60% 1RM	-	-	-	3–5 sets				
					60% 1RM	14 * 90	131.2 ± 12.8	Inflated during the exercise and deflated during the rest periods					
Laurentino et al. (2022)	23.6 ± 6	73.8 ± 12		10	80% 1RM	-	-	-	4 * 8	1.5 min between set.	8	2	CSA; 1RM; Hormones; Lactate concentration
	20.0 ± 4.5	72.1 ± 11.9		9	20% 1RM	17.5 * 92	80% of predicted arterial occlusion pressure (94.8 ± 10.3 mmHg)	Inflated for the entire exercise protocol	4 * 15	1 min between set.			
Lixandrão et al. (2015)	29.2 ± 9.9	74.9 ± 7.7	24.6 ± 2.7	9	80% 1RM	-	-	-	2–3 * 10	1 min between set.	12	2	CSA; 1RM.
	26.1 ± 7.6	80.6 ± 19.7	25.9 ± 5.6	11	20% 1RM	9.2 * 17.5	40% occlusion pressure (55.5 ± 7.6)	Inflated for the entire exercise protocol	2–3 * 15				
	28.9 ± 8.7	75.3 ± 10.7	24.6 ± 3.3	14	20% 1RM	9.2 * 17.5	80% occlusion pressure (109.6 ± 9.4)	Inflated for the entire exercise protocol	2–3 * 15				
	26.1 ± 7.6	74.7 ± 9.5	24.7 ± 2.1	8	40% 1RM	9.2 * 17.5	40% occlusion pressure (54.5 ± 4.6)	Inflated for the entire exercise protocol	2–3 * 15				
	28.9 ± 9.2	78.9 ± 20.7	25.0 ± 5.8	10	40% 1RM	9.2 * 17.5	80% occlusion pressure (105.0 ± 18.5)	Inflated for the entire exercise protocol	2–3 * 15				

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TABLE 3 (*Continued*) Summary of participant characteristics and trial characteristics of included studies.

Study	Participant characteristics				Trial characteristics								
	Age (yr)	Body weight (kg)	BMI [kg·m]	Sample Size	Intervention	Tourniquet (width * length, cm)	The occlusion pressure	Tourniquet application time	Training protocol	Rest	Duration (weeks)	Frequency (per week)	Outcomes
Madarame et al. (2008)	21.9 ± 4.2	60.7 ± 5.1		7	30% 1RM	4 * 175	-	-	30/15/15/15	0.5 min between set.	10	2	CSA; 1RM.
	21.6 ± 2.4	58.8 ± 3.8		8	30% 1RM		160–240 mmHg	Inflated for the entire exercise protocol					
Ozaki et al. (2013)	24 ± 1	62.3 ± 2.9	21.4 ± 0.8	9	75% 1RM	-	-	-	3 * 10	2–3 min between set.	6	3	CSA; 1RM; carotid arterial compliance; resting blood pressure
	23 ± 0	63.9 ± 2.4	21.7 ± 0.8	10	30% 1RM	3	80–130 mmHg	Inflated for the entire exercise protocol	30/15/15/15	0.5 min between set.			
Reece et al. (1985)	22.34 ± 3.34	79.49 ± 16.19		15	80% of 1RM	-	-	-	Volitional failure	2 min between set.	6	3	CSA; 1RM; muscle fiber type; volume load
	21.35 ± 2.71	70.41 ± 12.52		15	30% of 1RM	10	50% AOP	Inflated for the entire exercise protocol		1 min between set.			
Teixeira et al. (2022)	26 ± 4	82.6 ± 9.4		5	30% of 1RM	-	-	-	3 * 15	1 min of rest between sets	3	2	CSA; 1RM.
					30% of 1RM	9 * 18	80% of AOP - 102 mmHg	Inflated for the entire exercise protocol					
Vechin et al. (2015)	62.0 ± 3.0	68.7 ± 15.3		8	70%–80% of 1RM	-	-	-	4 * 10	1 min of rest between sets	12	2	CSA; 1RM.
	65.0 ± 2.0	79.3 ± 17.9		8	20%–30% of 1RM	18	50% of AOP - 71 ± 9 mmHg	Inflated for the entire exercise protocol	30/15/15/15				
Yasuda et al. (2014)	67.7 ± 6.0	53.4 ± 9.1	21.3 ± 2.9	10	-	-	-	-	-	-	-	-	CSA; 1RM; arterial function tests (resting blood pressure et.); blood sampling and biochemical analyses
	71.3 ± 7.1	53.4 ± 9.3	20.8 ± 2.6	19	20%–30% of 1RM	5	270 mmHg	Inflated for the entire exercise protocol	30/20/15/10	0.5 min rest between each series (knee extension) 1.5 min rest between each series (leg press)	12	2	

"Training protocol" refers to the design of the resistance training program, including the number of sets and repetitions or the total number of repetitions for each exercise. "Rest" refers to the rest period between sets during each training session. "Duration (weeks)" indicates the length of the entire training program in weeks. "Frequency (per week)" denotes how often training sessions occur each week. "Outcomes" refer to the main results or findings of each study.

3.3 Participant and trial characteristics

A total of 28 intervention groups from the 20 studies were reported in the analysis. The overall meta-analysis of the 20 studies included 515 participants, with study sizes varying from 4 to 19 subjects. Participant demographics revealed an age of 29.92 ± 2.22 (95% CI, 25.56–34.27), an body weight of 69.97 ± 1.59 (95% CI, 66.85–73.08, Q statistic = 52.75, *P* for heterogeneity = 0.07), and a BMI of 23.89 ± 0.66 (95% CI, 22.60–25.18, Q statistic = 65.98, *P* for heterogeneity <0.0001). Table 3 shows the participant characteristics and trials characteristics of the 20 included studies that met the selection criteria.

The current BFR training protocol is based on traditional resistance training protocol standards. The frequency of training sessions among the included studies varied between 2 and 4 times a week, with only one study implementing a training frequency of 4 times per week. Regarding the intensity of BFR combined with resistance training, a range of 20%–80% of 1 RM was observed among the intervention groups in the included studies. Among these groups, 23 intervention groups had intensities below 60% of 1 RM, indicating low-intensity resistance training (Schoenfeld et al., 2017). Only 2 intervention groups had intensities of 60%–80% of 1 RM, suggesting middle-intensity training. The remaining groups exhibited the BFR of 80% of 1RM, representing high-intensity training. Notably, the limited number of middle-intensity groups precluded specific meta-regression analysis. Therefore, these groups were amalgamated with the high-intensity groups as "other intensity with BFR" for further analysis. Considering the notable disparity in other trial characteristics across intervention groups, these were treated as covariates in subsequent meta-regression analyses.

It was observed that the intervention groups in the included studies utilized different types of tourniquets, with only one study (Brumitt et al., 2021b) omitting specific details regarding the tourniquet used. These tourniquets were tailored in length to match the cross-sectional area of participants' arms or legs. Consequently, the present study analyzed the influence of tourniquet width on BFR training. In addition to blood pressure monitor's accompanying pressurized belt, two different types of tourniquet products were applied in different studies, including the *Delphi Personalized Tourniquet System* with a tourniquet width of 11.43 cm in two studies (Bradley et al., 2022; Colapietro, 2023) and *Hokanson TD312 Calculating Cuff Inflator* with a tourniquet width of 6 cm in another two studies (Hackney et al., 2016; Cook and Cleary, 2019). In addition, 14 studies (20 intervention groups) had tourniquets inflated throughout training, and 6 studies (8 intervention groups) inflated the tourniquets during exercise and deflated them during the rest periods.

3.4 Effect estimates of BFR intervention to NOBFR intervention from meta-analysis

3.4.1 Heterogeneity and possible publication bias

The fixed-effect and random-effects meta-analyses were performed to assess the overall heterogeneity. The assessment revealed a moderate heterogeneity (I^2 = 41%, P = 0.01) for muscle thickness results across the studies and a low heterogeneity (I^2 = 0%, P = 0.90) for the muscle strength results. The funnel plot of muscle thickness results highlighted significant heterogeneity in one studies (Yasuda et al., 2014) (Figure 3A), and the Egger's test results indicated a lack of statistically significant asymmetry in the funnel plot (t = 1.43, df = 26, P = 0.16). Subsequently, the forest plot of sensitivity analysis showed that one study (Yasuda et al., 2014) significantly affected the robustness of the overall results, whereas two studies (Kacin and Strazar, 2011; Hackney et al., 2016) with a high risk assessed by RoB 2 did not impact the overall robustness (Figure 3B). Upon the exclusion of the study contributing to high heterogeneity, the overall heterogeneity reduced to a low level across all intervention groups (I^2 = 0%, P = 1.00) (Figure 4). Both the funnel plot and the forest plot of sensitivity analysis for muscle strength showed that none of the studies significantly affected the robustness of the overall results (Figures 4A, B). The Egger's test did not detect significant asymmetry in the funnel plot.

3.4.2 Subgroup meta-analysis of intervention intensity

The meta-analysis findings uncovered no significant discrepancy between resistance training with BFR and conventional resistance training in terms of enhancements in muscle thickness and strength. The overall contrast in muscle thickness improvement between BFR and conventional training stood at 0.11 (95% CI: −0.08–0.29, I^2 = 0%), indicating a no significance impact of conventional training on muscle thickness improvement. However, this difference was not statistically significant (z = 1.03, P = 0.302). Subgroup analysis revealed that BFR training combined with other intensity resistance training displayed a better effect on muscle thickness improvement (0.00, 95% CI: −0.53–0.52, I^2 = 0%) than BFR training with low-load resistance training (0.12, 95% CI: −0.07–0.32, I^2 = 0%). Nonetheless, this disparity failed to reach statistical significance ($\aleph^2 = 0.19, df = 1, p = 0.66$), as shown in Figure 5.

Regarding muscle strength improvement, the overall difference between BFR and routine resistance exercise was −0.07 (95% CI: −0.25–0.12, I^2 = 0%). This suggested that resistance exercise with BFR marginally surpassed routine resistance exercise in enhancing muscle strength (z = 0.74, P = 0.461). Subgroup meta-analysis showed that BFR combined with other intensity resistance exercise exhibited a better improvement effect on muscle strength (−0.02, 95% CI: −0.62–0.58, I^2 = 0%) than the low-intensity resistance exercise with BFR (−0.07, 95% CI: −0.27–0.12, I^2 = 0%). However, this difference did not reach statistical significance ($\aleph^2 = 0.03, df = 1, p = 0.87$), as depicted in Figure 6.

3.4.3 Meta-regression for BFR intervention

The meta-regression analysis incorporated a total of 7 variables to examine their effects on muscle thickness and strength improvement (see Tables 4, 5). The regression models are presented in Figure 7. The meta-regression results indicated that none of the moderators exhibited statistically significant links with muscle thickness improvement (P > 0.05). Only the occlusion pressure of tourniquets showed a marginal effect on muscle thickness improvement (coefficient estimate = 0.006, 95% CI = 0–0.012, adjusted R^2 = 0.30), which was not statistically significant (P = 0.057). The regression model suggested a slight increase in muscle thickness with increased tourniquet occlusion pressure (see

Figure 7). Conversely, the remaining moderators did not statistically significant improve muscle thickness. Furthermore, the moderators did not yield significant impacts on muscle strength improvement ($P > 0.05$. Adjusted $R^2 = 0$) (see Table 5).

4 Discussion

This meta-analysis aimed to assess the efficacy of muscle thickness and strength improvement by comparing resistance training combined with BFR to traditional resistance training. The comprehensive analysis revealed no significant difference between these two intervention methods. Notably, resistance training with BFR at other intensities (middle- and high-intensity) marginally outperformed low-intensity resistance with BFR in muscle strength and thickness improvement. However, no significant difference was noted in this regard between higher-intensity and lower-intensity resistance with BFR. These findings suggest that from a safety standpoint, higher-intensity resistance exercises with BFR might not be imperative for fragile populations. Moreover, the meta-regression results suggested a potential impact of tourniquet occlusion pressure on intervention outcomes, while trial characteristics extracted from literature review showed no significant association with muscle thickness and strength improvement. Nevertheless, these trial characteristics provide crucial reference information for establishing standards for BFR combined with resistance training in the future.

The meta-analysis results further revealed that resistance training coupled with BFR exerted a comparable influence to traditional resistance on muscle strength and thickness improvement. Although high-intensity resistance training stands out as the most efficacious method for enhancing muscle strength and thickness, its applicability is constrained by potential risks, especially for fragile populations. Several studies (Krzysztofik et al., 2019; Koc et al., 2022; Krzysztofik et al., 2022) have indicated that resistance training with BFR offers a promising alternative to traditional methods, demonstrating comparable effects. Older adults and hospitalized patients commonly grapple with muscle loss and weakness owing to a lack of exercise (Ruiz et al., 2008), often associated with a decline in type II muscle fibers (Park et al., 2022). High-intensity resistance training, although effective in improving muscle strength through neural adaptions, may pose injury risks, particularly for old adults or patients, given the acute hemodynamic response it triggers (Nascimento et al., 2022). The repeated elevation in blood pressure increases endothelial shear, thrombin, and fibrin (Hansen et al., 2022), heightening the risk of venous thrombosis (Hansen et al., 2022). In contrast, resistance training coupled with BFR stimulates muscular hypertrophy by recruiting type II muscular fibers due to the localized hypoxia environment, thus enhancing muscle strength (Pour et al., 2017). This method, nevertheless, has also been reported to elevate blood pressure and provoke certain atypical vascular reactions (Nascimento et al., 2022), such as ischemia-reperfusion injury (Cristina-Oliveira et al., 2020). However, a recent study (Nascimento et al., 2019) reported contrasting findings, suggesting that resistance training with BFR did not induce coagulation activity; instead, it demonstrated an increase in fibrinolytic activity. This suggests that this intervention may not pose an elevated risk of thrombus formation. In addition, resistance training with BFR may have potential effects on endothelial function and vascular regeneration (Zhang et al., 2022), although further evidence is needed for confirmation. Despite these considerations, resistance training with BFR has already been applied in some clinical settings for functional rehabilitation (Hughes et al., 2019; Killinger et al., 2020; Anandavadivelan et al., 2024). However, aspects such as training intensity and some trial characteristics necessitate further elucidation.

The standardization of resistance training protocols with BFR remains elusive, with factors like training intensity, duration, and tourniquets specifications during the intervention potentially influencing intervention effectiveness. In view of this, this study conducted subgroup meta-analysis and meta-regression to examine the relationships between trial characteristics and muscle hypertrophy. The subgroup analysis aimed at assessing the influence of different intensities on muscle changes. Notably, limited research has explored the effects of other intensities, especially high-intensity resistance training with BFR, on muscle changes, underscoring the necessity for further validation of its impact. Among the studies included in our analysis, only three (comprising four intervention groups) implemented moderate- (60%–80% of 1 RM) and high-intensity (over 80% of 1 RM) resistance training with BFR. Subgroup analysis was conducted to compare the effects of low-intensity (below 60% of 1 RM) resistance training with BFR against other intensities (moderate and high intensities) of resistance training with BFR, aiming to elucidate the differential effects on muscle changes. The results revealed no significant difference in muscle strength and thickness improvements between low-intensity and moderate- and high-intensity resistance training with BFR. Studies by Biazon et al. (2019); Laurentino et al. (2008) reported that high-intensity resistance training with BFR did not notably outperform high-intensity resistance training without BFR in inducing muscle hypertrophy. However, Barrett, 2017 discovered that 70% of 1 RM resistance training with BFR did not lead to greater muscle hypertrophy than moderate-to-intensity training alone during a 12-week training period. This discrepancy might be attributed to participant characteristics, as Barrett's study involved highly trained males, potentially limiting substantial gains in muscle strength and thickness compared to untrained populations. Differing trial characteristics, such as trial volume, might also play a role in this divergence. Barrent's study Barrett (2017) adjusted the training volume based on participants' individual conditions, such as premature fatigue; in contrast, studies by Biazon et al. (2019); Laurentino et al. (2008) employed a fixed training protocol for each participant.

Further substantiation is required to affirm the impact of moderate- and high-intensity resistance training with BFR on muscle hypertrophy. Compared to low-intensity resistance training with BFR, high-intensity resistance training with BFR presnets heightened challenges to participants' physical condition and exerts greater stress on the cardiovascular system, potentially posing risk during training (Hansen et al., 2022). In light of current findings, advocating for the application of low-intensity resistance training with BFR in clinical settings and for populations unable to endure high-intensity training seems prudent. Bradley et al. (2022) demonstrated that low-load BFR training (30% 1 RM) resulted in lower Rating of Perceived Exertion (RPF) scores than training at 70% 1RM. For individuals lacking training experience or unable to withstand high-intensity training, implementing low-load training with BFR

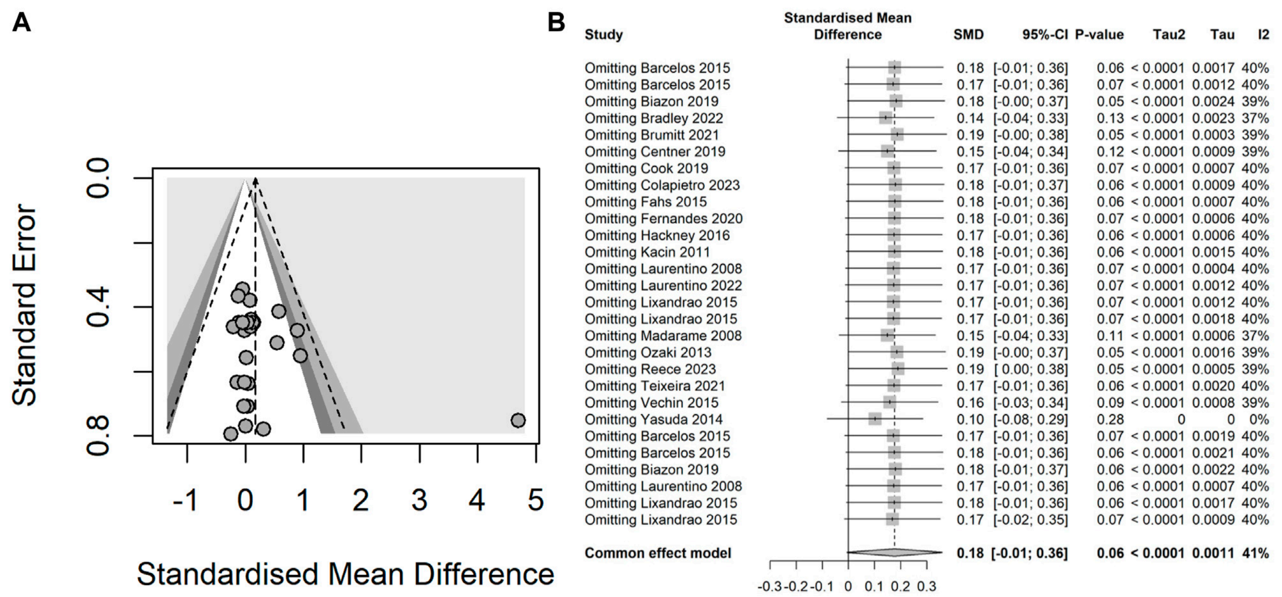

FIGURE 3
(A) Funnel plot illustrating the heterogeneity of studies within the intervention groups concerning muscle thickness results; **(B)** Forest plot demonstrating the effect on the overall robustness of the results upon the exclusion of each individual intervention for muscle thickness.

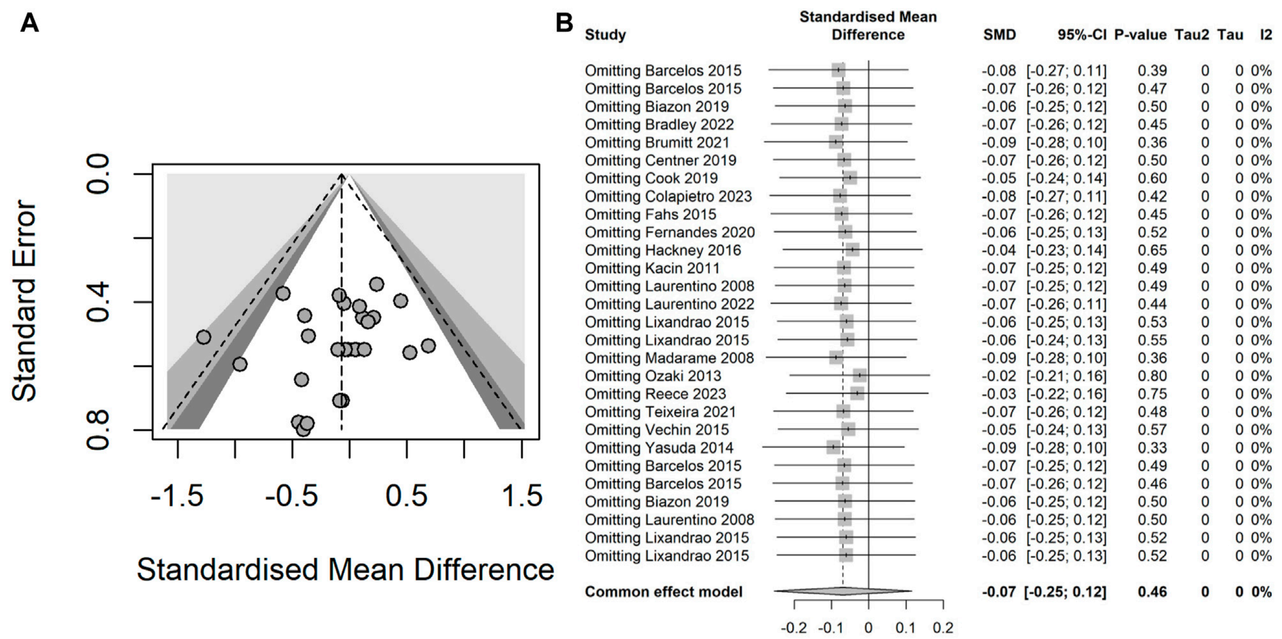

FIGURE 4
(A) Funnel plot illustrating the heterogeneity of studies within the intervention groups concerning muscle strength results; **(B)** Forest plot demonstrating the effect on the overall robustness of the results upon the exclusion of each individual intervention for muscle strength.

may alleviate discomfort during training. Additionally, low-intensity resistance training with BFR exerts notably less strain on joints and soft tissues than high-intensity resistance training (Patterson et al., 2019). It is worth noting that 20% 1 RM is equivalent to the intensity of daily activities (Almeida et al., 2022), but studies involving training intensities below 20% 1 RM are currently lacking. Training at intensities lower than 20% 1 RM may not induce sufficient biological pressure to stimulate muscle hypertrophy. Therefore, low-intensity resistance training with BFR is recommended for daily training due to its safety and effectiveness.

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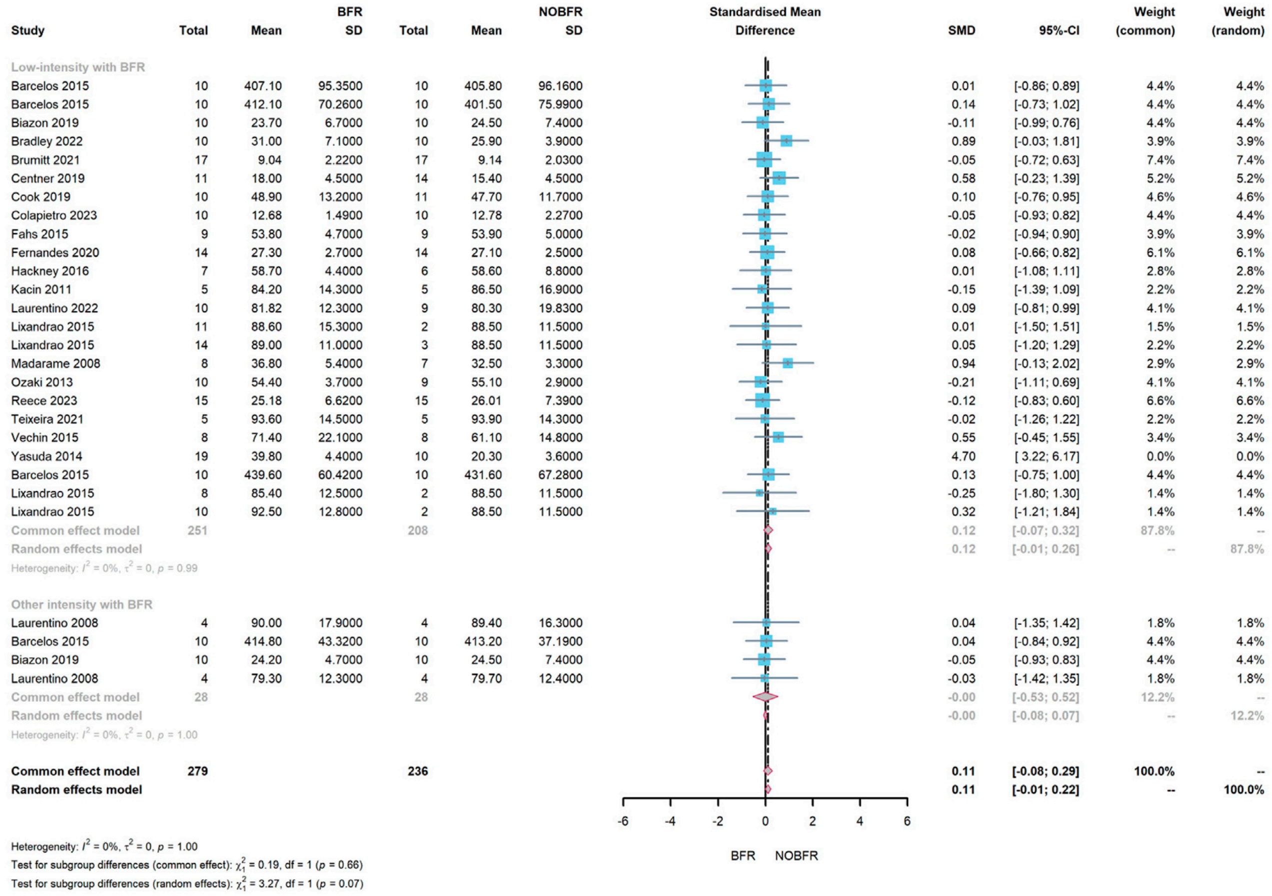

FIGURE 5
Forest plot demonstrating a subgroup meta-analysis assessing the effect of BFR combined with resistance training at low and other intensities on muscle thickness improvement.

The meta-regression results revealed an absence of significant impact from the training protocol characteristics on the outcomes. This observation may be attributed to the minor variations in training protocols among the studies included in our analysis. The intervention protocols in these studies were derived from modifications to traditional resistance training foundation, prescribing a training frequency of 2-3 sessions per week with a minimum duration of 4 weeks. Notably, evidence from several studies suggests that this approach can elicit muscle hypertrophy within 2 weeks (Hill et al., 2018; Teixeira et al., 2022). Six studies adhered consistently to a specific design for BFR training sets and repetitions of 30/15/15/15 (four sets). In addition to the details of the training protocols, certain characteristics of the tourniquet used during training may also wield influence over the intervention outcomes.

In addition to training intensity, our meta-regression explored the link between certain tourniquets characteristics and their effects on muscle hypertrophy. The analysis unvialed no significant association between deflating the tourniquet during rest periods and its impact on muscle hypertrophy. However, these findings were drawn from trials focusing on LI resistance training with BFR, with limited representation of other-intensity resistance training with BFR. Consequently, the existing evidence might not be sufficient to establish a definitive relationship between tourniquet inflation status and the effects of high-intensity resistance training with BFR on muscle hypertrophy. Laurentino et al. (2008), for instance, reported discomfort and early fatigue associated with inflated tourniquets during high-intensity resistance training, potentially influencing muscle hypertrophy improvements (Das and Paton, 2022). The practice of deflating tourniquets during rest periods may contribute to maintaining adequate training volume for muscle hypertrophy in certain contexts (Barrett, 2017).

The width and occlusion pressure of tourniquets have surfaced as potential influencers of intervention efficacy. Presently, there are no standardized criteria for tourniquet usage in BFR training. Among the literature included, only two companies offered blocking tourniquet products tailored for training, each with differing specifications. While tourniquet width did not exhibit a significant association with muscle changes, it potentially impacted the intervention's effectiveness. The regression model indicated slight reduction

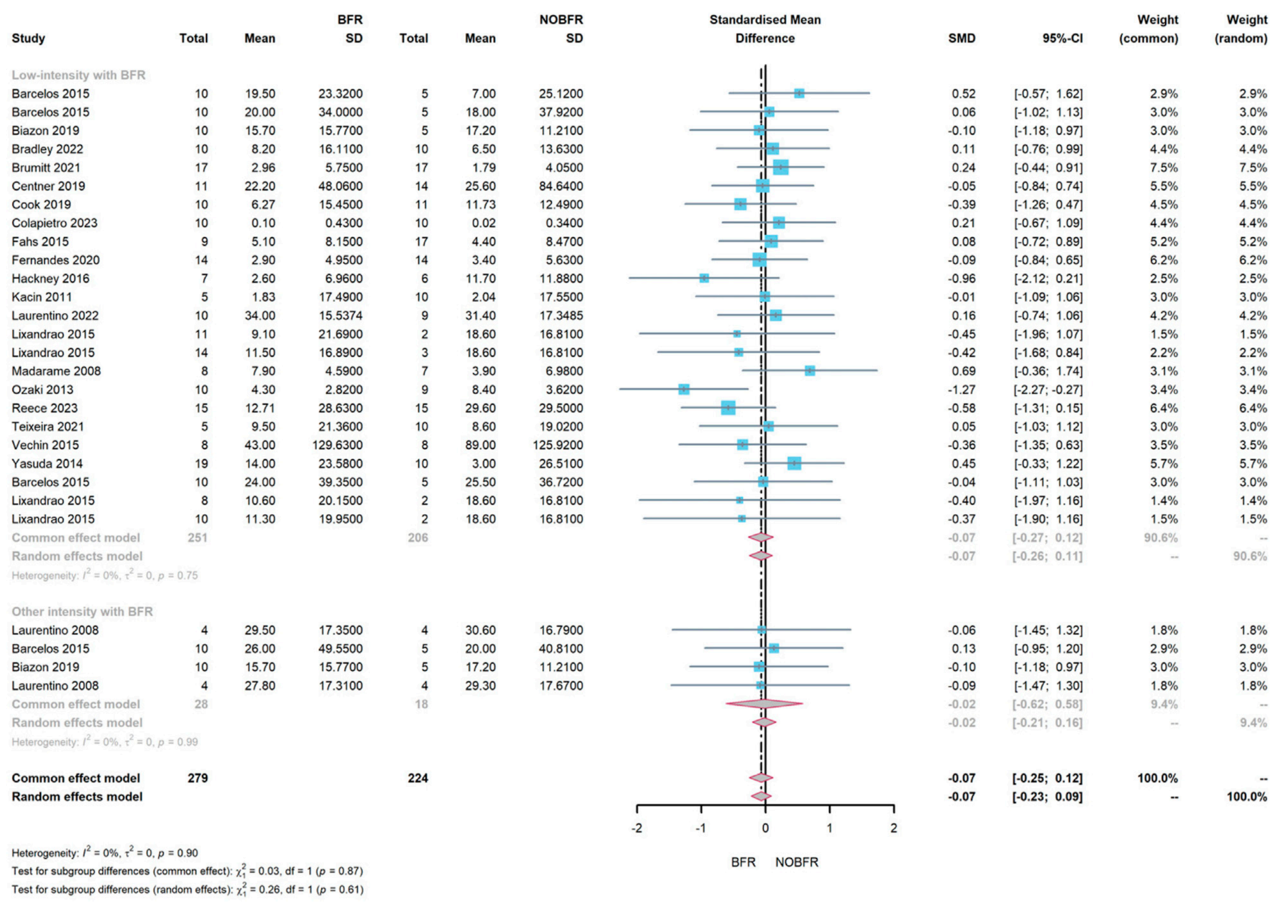

FIGURE 6
Forest plot illustrating a subgroup meta-analysis evaluating the effect of BFR combined with resistance training at low and other intensities on muscle strength improvement.

TABLE 4 Meta-regression of moderators concerning the effects of BFR combined with resistance training on muscle thickness improvement.

Variable	Number of intervention groups	Coefficient	Std.err	t	p	95% CI	Adjusted R^2
Intervention intensity	28	−0.213	0.387	−0.55	0.587	−1.008, 0.582	0
Training volume	24	0.003	0.008	0.41	0.685	−0.013, 0.020	−42.62%
Rest duration	27	0.149	0.356	0.42	0.680	−0.584, 0.882	−94.62%
Training sessions	28	0.009	0.013	0.65	0.524	−0.019, 0.036	0
Tourniquet width	27	−0.026	0.028	−0.93	0.361	−0.084, 0.032	−79.63%
Occlusion pressure	20	0.006	0.003	2.03	0.057	0, 0.012	30.23%
Tourniquet application time	28	−0.164	0.287	−0.57	0.572	−0.753, 0.425	0

in intervention improvement with an increase in tourniquets width. Although direct investigation into the effect of tourniquet width on intervention effectiveness was lacking, previous research suggested that wider tourniquets may exert greater occlusion pressure due to decreased pressure required to occlude blood vessels. Loenneke et al. (2012) observed that the pressure required to occlude blood flow decreases proportionally with increasing cuff width. However, it is essential to note that these results may be influenced by the cuff material in the study, as narrower tourniquets demonstrated better elasticity compared to wider ones. Thus, wider tourniquets might induce better localized hypoxia, potentially enhancing muscle growth stimulation (Michal et al., 2020). The studies encompassed in our analysis did not account for different occlusion pressures resulting from varying widths, which could potentially affect the intervention's effectiveness. This emphasizes the need for future

TABLE 5 Meta-regression of moderators concerning the effects of BFR combined with resistance training on muscle strength improvement.

Variable	Number of intervention groups	Coefficient	Std.err	*t*	*p*	95% CI	Adjusted R^2
Intervention intensity	28	0.054	0.322	0.17	0.869	−0.608, 0.716	0
Training volume	24	−0.001	0.005	−0.23	0.818	−0.011, 0.009	0
Rest duration	27	−0.046	0.238	−0.19	0.847	−0.537, 0.444	0
Training sessions	28	−0.002	0.010	−0.21	0.834	−0.023, 0.018	0
Tourniquet width	27	−0.004	0.020	−0.19	0.848	−0.045, 0.038	0
Occlusion pressure	20	0.004	0.002	2.09	0.051	0, 0.008	0
Tourniquet application time	28	−0.009	0.213	−0.04	0.966	−0.446, 0.428	0

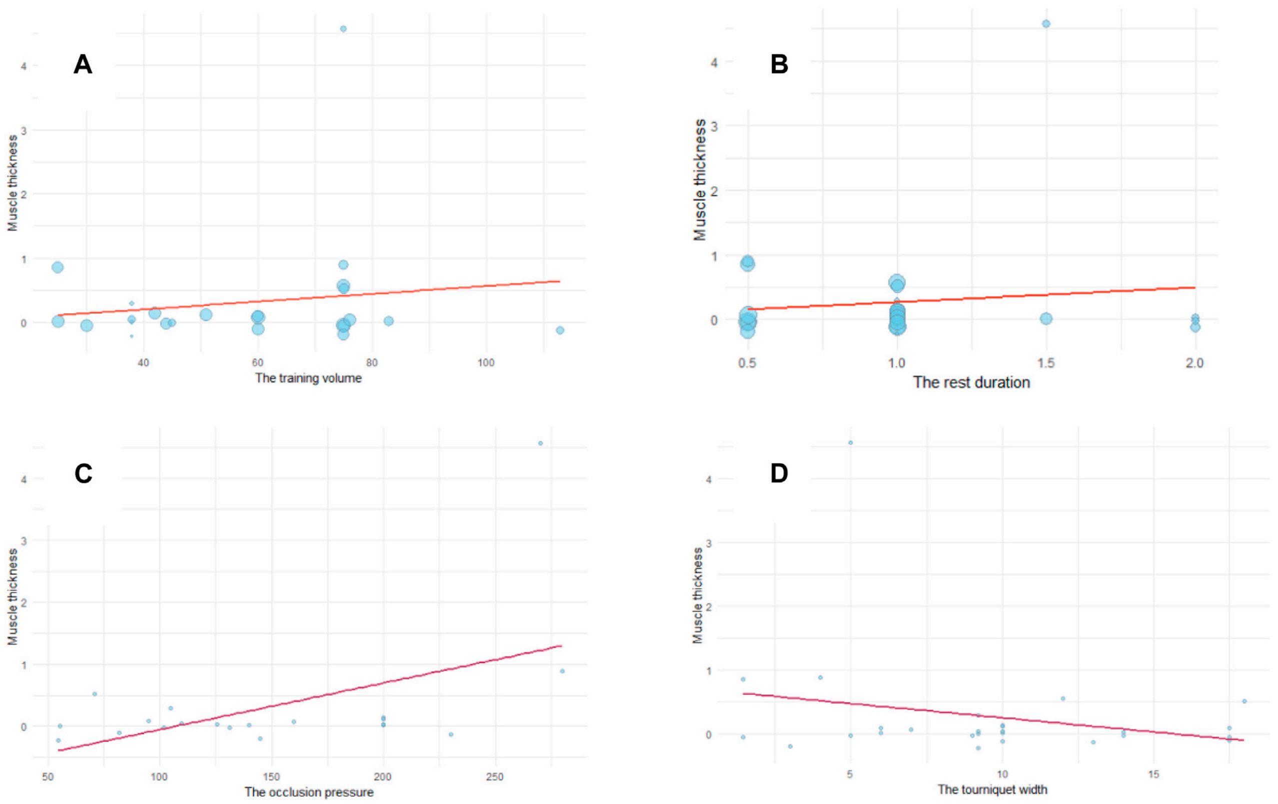

FIGURE 7
Meta-regression modelling of the effects of **(A)** training volume **(B)** training rest duration **(C)** tourniquet occlusion pressure, and **(D)** tourniquet width on muscle thickness improvement by BFR combined with resistance training.

research to explore the synergistic effects of tourniquet width and pressure, as well as the influence of tourniquet material on intervention outcomes. Additionally, considering that a narrower cuff may lead to localized muscle damage due to increased strain (Das and Paton, 2022), it follows that a wider cuff would be more practical for application.

Regarding the pressure applied by tourniquets, the results of the meta-regression indicated that it did not exhibit a significant association with intervention outcomes. However, the regression model highlighted that increased occlusion pressure correlated with more effective muscle hypertrophy improvement. Higher restriction pressure (70%–100% LOP) may indicate a lower blood supply, leading to increased metabolic strain during exercise, potentially resulting in an enhanced muscle strength and hypertrophy (Fabero-Garrido et al., 2022b; Cognetti et al., 2022). Nevertheless, careful selection of the occlusion pressure is crucial. Most studies in our analysis utilized an arterial occlusion pressure (AOP) ranging from 40% to 80%. It has been suggested that an AOP of 50%–80% is optimal for BFR training (Das and Paton, 2022), and an AOP exceeding 80% may elevate the risk of adverse events during patient training, such as the potential induction of venous thrombosis (Stavres et al., 2018). Furthermore, higher cuff pressure may lead to discomfort, post-exercise soreness, and reduced total exercise volume. Notably, 8 studies (40%) included in our analysis did not apply individualized pressure settings to participants, potentially resulting in training-related pain (Koc et al., 2022). Hence, careful consideration regarding the width and occlusion pressure of tourniquets is vital during training interventions to minimize potential adverse effects while achieving desired muscle growth.

5 Conclusion

Low intensity resistance training with BFR is a safe and effective training program. This training method induces muscle hypertrophy in a short period of time and alleviates the process of muscle wasting by stimulating and engaging type II muscle fibre contractions. It also reduces the risk of venous thrombosis. However, it is important to note that although this training programme is similar to high-intensity resistance training, it may place a greater cardiovascular workload, which may lead to adverse events. In order to improve the improvement in muscle strength and dimensions with this intervention protocol, this study analysed the results of existing studies. Based on the results, this study suggests that the prescription of the programme could be guided by the following parameters: 2-3 training sessions per week at an intensity of 20%–40% of 1 RM. In addition, it is recommended to use a wider cuff and to apply 50%–80% of the arterial occlusion pressure during training to stimulate improvements in muscle strength and thickness. In addition, releasing tourniquet pressure during rest periods is beneficial to reduce participant discomfort during training.

While our investigation provides valuable insights, the limited number of studies examining the combination of high-intensity resistance training and BFR restricts the generalization of our findings, particularly in the context of high-intensity training. Furthermore, our findings highlight the need for further exploration into the effects of tourniquet width and pressure on intervention outcomes. Subsequently, studies should endeavor to investigate the synergistic effects of tourniquet pressure and width on intervention effects. Additionally, the characteristics of tourniquet materials, such as elasticity, and their impact on intervention outcomes remain an understudied area that warrants attention.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

FM: Data curation, Investigation, Methodology, Writing–original draft, Writing–review and editing. JH: Data curation, Methodology, Writing–original draft. YW: Methodology, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Commentary: Blood flow restriction combined with resistance training on muscle strength and thickness improvement in young adults: a systematic review, meta-analysis, and meta-regression

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A Commentary on
Blood flow restriction combined with resistance training on muscle strength and thickness improvement in young adults: a systematic review, meta-analysis, and meta-regression

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Introduction

Systematic reviews (SRs) are studies that aim to provide a comprehensive and impartial synthesis of multiple studies on a given topic, bringing together "all" relevant evidence in a single document to answer specific research questions (Rother, 2007; Aromataris and Pearson, 2014). SRs are widely useful for health professionals who has limited time to read several articles on a given topic, but carry out their practice based on evidence. Therefore, it is essential that SRs are conducted with the methodological rigor expected of any research. Recently, a group of researchers conducted a SR and meta-analysis that aimed to evaluate the effects of resistance training (RT) with blood flow restriction (BFR) on strength and "muscle thickness" in healthy individuals (Ma et al., 2024). The topic explored in this study is highly relevant and valuable, and we commend the authors for their efforts. However, we believe that additional detail and attention to certain methodological aspects could enhance the interpretation of the results. In this document, we will be discussing some points that may have contributed to erroneous conclusions about the results presented in the study.

Study selection

It is recommended that eligibility criteria for study selection be based on the PICOS elements defined by the review question (Aromataris and Pearson, 2014). Although the researchers sought to follow this approach, crucial aspects were not adequately reported. We noted that some details regarding the interventions, such as load used during BFR training, duration, frequency, and characteristics of comparator conditions, were not fully reported. This omission makes it difficult to understand the criteria for study selection.

Assuming that the authors did not apply restrictions regarding the intervention time, it is possible to identify that certain studies (Yasuda et al., 2010; Fujita et al., 2008; Abe et al., 2005) that analyzed the effects of low-load RT (LL-RT) with short-term (1–3 weeks) and high weekly frequency of BFR on muscle hypertrophy and strength were not included (Ma et al., 2024). Furthermore, some studies that compared LL-RT with BFR *versus* high-load resistance training (HL-RT) were also not included (Kim et al., 2017; Galvao Pereira et al., 2019; Jessee et al., 2018; Buckner et al., 2020; Libardi et al., 2015; May et al., 2022). Given the eligibility criteria, it seems that including these studies could have provided a more comprehensive review. The absence of these studies suggests that there might be gaps in the selection process, which warrants careful interpretation of the results.

The search strategy adopted by the authors may justify the absence of certain studies. The combination of terms with the help of the Boolean operator "AND" may have limited the searches to studies that presented all the descriptors presented, including "resistance training", hypoxia and "blood flow restriction therapy" and the respective alternative terms adopted for each descriptor. Therefore, a study that presented only the terms "resistance training" and "blood flow restriction" may not be retrieved when adopting the search strategy adopted by Ma et al. (Aromataris and Pearson, 2014).

Another point that caught our attention is the fact that the authors seem to use the terms "muscle thickness" and "cross-sectional area" (CSA) as synonyms. Muscle thickness refers to the distance between a superficial and deep border of a muscle that is usually measured at specific sites along the muscle using ultrasound imaging (Miyachi et al., 2020). On the other hand, muscle CSA refers to the total area of muscle that is perpendicular to its length (Miyachi et al., 2020). Muscle CSA is typically assessed via magnetic resonance imaging or computer tomography and is thought to present a more accurate measure of total muscle size. In essence, muscle thickness provides a 2D analysis of a measure of muscle size at a particular point in the muscle belly whereas muscle CSA provides a 3D image of the total muscle size.

Risk of bias

The risk of bias in the studies included in the SR by Ma et al. (Ma et al., 2024) was assessed using the Cochrane Risk of Bias 2 (RoB 2) tool. The RoB two was used in a SR conducted by our research group, which compared the effect of LL-RT with BFR *versus* HL-RT (de Queiros et al., 2024).

Considering that our review had similar objectives to those of Ma et al. (Ma et al., 2024), some studies were included in both. Interestingly, there are inconsistencies between the reviews regarding the assessments of the risk of bias of these studies. In domain one of RoB 2 (bias due to the randomization process), the risk of bias rating was considered "low" in the SR of Ma et al. (Ma et al., 2024) for certain studies (Biazon et al., 2019; Centner et al., 2019; Laurentino et al., 2022; Reece et al., 2023; Ozaki et al., 2013), whereas in our review, such studies were rated as "some concerns". In our study, this rating is justified by the fact that none of these studies detailed the randomization process or mentioned allocation concealment.

In domain 4, biases related to outcome measurement, inconsistencies were also reported; Ma et al. (Ma et al., 2024) classified all studies included in their review as "low risk of bias". However, some studies did not report blinding of outcome assessors (Biazon et al., 2019; Laurentino et al., 2022; Reece et al., 2023; Ozaki et al., 2013; Vechin et al., 2015; Lixandrão et al., 2015). Considering the information presented, we speculate that the risk of bias assessment performed by Ma et al. (Ma et al., 2024) are not representative of the true risk of bias in the included studies.

Meta-analyses

When analyzing the characteristics of the studies included in the SR conducted by Ma et al. (Ma et al., 2024), it is possible to identify that some studies performed comparisons between LL-RT with BFR *versus* HL-RT, while other studies compared LL-RT with BFR *versus* LL-RT without BFR. We identified that the authors included all studies in a single meta-analysis, both for strength and muscle size. This could potentially obscure the effects of resistance training with BFR and impact the generalizability of the findings.

Discussion

The SR conducted by Ma et al. (Ma et al., 2024) might have excluded some eligible studies, which could affect the comprehensiveness of the review. In addition, we speculate that there are problems with the assessment of the risk of bias of the studies included in the review, which may lead to misleading conclusions about the quality of the evidence presented. Finally, we assert that the quantitative synthesis of the results of the studies was not done adequately, since the authors did not stratify the results according to the comparator. Therefore, we recommend that readers interpret the results with some caution, considering the potential limitations.

Author contributions

VQ: Writing–original draft. RA: Writing–review and editing. NR: Writing–review and editing. MF: Writing–review and editing. JV: Writing–review and editing. BC: Writing–review and editing. PD: Writing–review and editing.

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Conflict of interest

NR is the founder of THE BFR PROS, a BFR education company that provides BFR training workshops to fitness and rehabilitation professionals across the world using a variety of BFR devices.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Give it a rest: a systematic review with Bayesian meta-analysis on the effect of inter-set rest interval duration on muscle hypertrophy

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We systematically searched the literature for studies with a randomized design that compared different inter-set rest interval durations for estimates of pre-/post-study changes in lean/muscle mass in healthy adults while controlling all other training variables. Bayesian meta-analyses on non-controlled effect sizes using hierarchical models of all 19 measurements (thigh: 10; arm: 6; whole body: 3) from 9 studies meeting inclusion criteria analyses showed substantial overlap of standardized mean differences across the different inter-set rest periods [binary: short: 0.48 (95%CrI: 0.19–0.81), longer: 0.56 (95%CrI: 0.24–0.86); Four categories: short: 0.47 (95%CrI: 0.19–0.80), intermediate: 0.65 (95%CrI: 0.18–1.1), long: 0.55 (95%CrI: 0.15–0.90), very long: 0.50 (95%CrI: 0.14–0.89)], with substantial heterogeneity in results. Univariate and multivariate pairwise meta-analyses of controlled binary (short vs. longer) effect sizes showed similar results for the arm and thigh with central estimates tending to favor longer rest periods [arm: 0.13 (95%CrI: −0.27 to 0.51); thigh: 0.17 (95%CrI: −0.13 to 0.43)]. In contrast, central estimates closer to zero but marginally favoring shorter rest periods were estimated for the whole body [whole body: −0.08 (95%CrI: −0.45 to 0.29)]. Subanalysis of set end-point data indicated that training to failure or stopping short of failure did not meaningfully influence the interaction between rest interval duration and muscle hypertrophy. In conclusion, results suggest a small hypertrophic benefit to employing inter-set rest interval durations >60 s, perhaps mediated by reductions in volume load. However, our analysis did not detect appreciable differences in hypertrophy when resting >90 s between sets, consistent with evidence that detrimental effects on volume load tend to plateau beyond this time-frame.

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KEYWORDS

rest period, recovery interval, muscle growth, muscle development, muscle thickness, muscle cross-sectional area

Introduction

It has been proposed that the manipulation of resistance training (RT) program variables can help to optimize skeletal muscle hypertrophy (1). However, because of the onerous time commitment involved in conducting directly supervised longitudinal RT protocols, most research on the effects of manipulation of program variables have involved relatively small sample sizes. Thus, meta-analytic techniques that pool and explore the results of all relevant studies on a given topic can provide additional insights on the topic by quantifying the magnitude of effects, which may help to guide prescription. To date, relatively recent meta-analyses have investigated the effect of manipulating a variety of RT program variables on muscle hypertrophy outcomes including load (2), volume (3), frequency (4), and proximity to failure (5), furthering our understanding of their practical implications.

The rest interval, operationally defined herein as the duration between sets during RT, is thought to be an important variable that has implications for exercise prescription (6). The National Strength and Conditioning Association recommends relatively short rest periods (30–90 s) to optimize muscle hypertrophy (7). This is largely based on acute research showing that short rest periods enhance the post-exercise hormonal response to RT, which has been theorized to promote muscular adaptations (8). However, emerging research suggests that transient post-exercise hormonal elevations may not play an important role in eliciting muscle hypertrophy (9, 10), which calls into question the benefit of short rest intervals for optimizing muscle development. Moreover, there is an inverse relationship between rest interval duration and the magnitude of load lifted in subsequent sets, whereby shorter rest periods necessitate larger reductions in load to complete a given number of repetitions compared to longer rest periods (11, 12). Considering that mechanical tension is a primary mechanism for promoting RT-induced hypertrophy (13), such reductions in volume load may actually compromise muscular adaptations. Indeed, McKendry et al. (14) reported that short rest intervals (1 min) blunted the myofibrillar protein synthetic response to RT compared to longer rest intervals (5 min) despite higher acute testosterone elevations in the short-rest condition; predictably, volume load decreased to a greater extent with shorter rest.

Longitudinal research investigating the influence of rest intervals on muscle hypertrophy has been largely equivocal. A systematic review by Grgic et al. (15) concluded that both short and long inter-set rest periods are viable options for untrained individuals seeking to optimize hypertrophy, but that longer durations may be advantageous for those with previous RT experience. It should be noted that this review was published in 2017 and additional research has been conducted on the topic since that time. Moreover, no study to date has endeavored to quantify the magnitude of effect between different rest interval conditions to determine if differences may be practically meaningful for RT prescription. Therefore, the purpose of this study was to systematically review the literature and perform a Bayesian meta-analysis of the existing data on the effects of rest interval duration during RT on measures of muscle hypertrophy.

Materials and methods

We conducted this review in accordance with the guidelines of the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" (PRISMA). The study was preregistered on the Open Science Framework (https://osf.io/ywevc).

Literature search strategy

To identify relevant studies for the topic, we conducted a comprehensive search of the PubMed/MEDLINE, Scopus, and Web of Science databases using the following Boolean search syntax: ("rest interval" OR "inter-set rest" OR "interset rest" OR "rest period*" OR "rest between sets" OR "resting interval" OR "resting period" OR "recovery interval") AND ("resistance training" OR "resistance exercise" OR "weight lifting" OR "weightlifting" OR "strength exercise" OR "strength training" OR "strengthening" OR "resistive exercise" OR "resistive training") AND ("muscle hypertrophy" OR "muscular hypertrophy" OR "muscle mass" OR "lean body mass" OR "fat-free mass" OR "fat free mass" OR "muscle fiber" OR "muscle size" OR "muscle fibre" OR "muscle thickness" OR "cross-sectional area" OR "computed tomography" OR "magnetic resonance imaging" OR "ultrasound" OR "DXA" OR "DEXA" OR "bioelectrical impedance analysis"). As previously described (16), we also screened the reference lists of articles retrieved and applicable review papers, as well as tapped into the authors' personal knowledge of the topic, to uncover any additional studies that might meet inclusion criteria (17). Moreover, we performed secondary "forward" and "backward" searches for citations of included studies in Google Scholar.

As previously described, the search process was conducted separately by 3 researchers (LG, AS and MR). Initially, we screened all titles and abstracts to uncover studies that might meet inclusion/exclusion criteria using online software (https://www.rayyan.ai/). If a paper was deemed potentially relevant, we scrutinized the full text to determine whether it warranted inclusion. Any disputes that could not be resolved by the search team were settled by a fourth researcher (BJS). The search was finalized in March 2024.

Inclusion criteria

We included studies that satisfied the following criteria: (a) had a randomized design (either within- or between-group design) and compared different inter-set rest interval durations for estimates of pre-/post-study changes in lean/muscle mass using a validated measure (dual-energy x-ray absorptiometry [DXA], bioelectrical impedance analysis, magnetic resonance imaging [MRI], computerized tomography [CT], ultrasound, muscle biopsy or limb circumference measurement) in healthy adults (≥18 years of age) of any RT experience while controlling all other training variables (in the case of volume, this represented either sets per muscle per session or volume load per session [i.e., sets × repetitions × load][1]; (b) involved at least 2 RT sessions per week for a duration of at least 4 weeks; (c) published in a peer-reviewed English language journal or on a preprint server. We excluded studies that (a) included participants with co-morbidities that might impair the hypertrophic response to RT (musculoskeletal disease/injury/cardiovascular impairments); (b) employed unequal dietary supplement provision (i.e., one group received a given supplement and the other received an alternative supplement/placebo).

Data extraction

Three researchers (KD, EA and MW) independently extracted and coded the following data for each included study: Author name (s), title and year of publication, sample size, participant characteristics (i.e., sex, training status, age), description of the training intervention (duration, volume, frequency, modality), nutrition controlled (yes/no), method for lean/muscle mass assessment (i.e., DXA, MRI, CT, ultrasound, biopsy, circumference measurement), and mean pre- and post-study values for lean/muscle mass with corresponding standard deviations. In cases where rest periods fluctuated over time, we averaged values to report a mean. In cases where measures of changes in lean/muscle mass were not reported, we attempted to contact the corresponding author(s) to obtain the data as previously described (16). If unattainable, we extracted the data from graphs (when available) via online software (https://automeris.io/WebPlotDigitizer/). To account for the possibility of coder drift, a third researcher (AS) recoded 30% of the studies, which were randomly selected for assessment (18). Per case agreement was determined by dividing the number of variables coded the same by the total number of variables. Acceptance required a mean agreement of 0.90. Any discrepancies in the extracted data were resolved through discussion and mutual consensus of the coders.

Methodological quality

The methodological quality of the included studies was assessed using the "Standards Method for Assessment of Resistance Training in Longitudinal Designs" (SMART-LD) scale (16). The SMART-LD tool consists of 20 questions that address a combination of study bias and reporting quality as follows: general (items 1–2); participants (items 3–7), training program (items 8–11), outcomes (items 12–16), and statistical analyses (17–20). Each item in the checklist is given 1 point if the criterion is sufficiently displayed or 0 points if the criterion is insufficiently displayed. The values of all questions are summed, with the final total used to classify studies as follows: "good quality" (16–20 points); "fair quality" (12–15 points); or "poor quality" (≤11). Three reviewers (EE, AM and PAK) independently rated each study using the SMART-LD tool; any disputes were resolved by majority consensus. We included all data irrespective of the study rating.

Statistical analyses

All meta-analyses were conducted within a Bayesian framework enabling the results to be interpreted more intuitively compared to a standard frequentist approach through use of probabilistic statements regarding parameters of interest (19). A Bayesian framework avoids dichotomous interpretations of meta-analytic results regarding the presence or absence of an effect (e.g., with p values), and instead places greater emphasis on describing the most likely values for the average effect (19) while addressing practical questions such as which inter-set rest interval duration is likely to create the greatest muscle hypertrophy. To facilitate comparisons across the inter-set rest interval spectrum, durations were categorized using two sets of cut-points. The first was a binary categorization of short (duration ≤ 60 s) and longer (duration > 60 s), and the second comprised four categories (short: duration ≤ 60 s; intermediate: 60 s < duration < 120 s; long: 120 s ≤ duration < 180 s; and very long: duration ≥ 180 s). These cutoffs are based on the general rest interval durations used across studies. Due to the use of different measurement technologies, effect sizes were quantified by using standardized mean differences (SMDs). To account for the small sample sizes generally used in strength and conditioning, a bias correction was applied (20). The primary measure for this meta-analysis was controlled magnitude-based SMDs obtained by subtracting the baseline change of one inter-set rest interval category from another and dividing by the pre-intervention pooled standard deviation (20). To assess the overall effectiveness of the interventions included, initial analyses were conducted using non-controlled SMDs (21). Interpretation of the magnitude of effect sizes was facilitated by comparison to small, medium, and large thresholds developed for strength and conditioning outcomes (22).

Three-level hierarchical models were used with inter-set rest interval included as a categorical variable to summarize the results using non-controlled SMDs. Pairwise (direct comparisons only) and network (direct and indirect comparisons) meta-analysis approaches were then used with controlled SMDs to compare across the binary and four category representations, respectively. Univariate analyses separated by measurement site (whole body, thigh, or arm) were also conducted. For the direct comparison, multivariate analysis was also conducted allowing for correlations between measurement sites. Network meta-analyses are becoming increasingly common in evidence synthesis and are most used to compare qualitatively different treatments where individual studies are unlikely to directly compare all levels (23). The technique calculates pairwise effect sizes from studies comparing two levels

[1]In cases where studies equated sets between conditions, fewer repetitions may have been performed in the shorter rest conditions over multiple sets of a given exercise.

(direct evidence) and generates indirect evidence comparing other levels through a common comparator (23). To summarize potential differences in hypertrophy across all inter-set rest interval categories in a network, the Surface Under the Cumulative Ranking curve (SUCRA (24); was used. For each category a SUCRA value expressed as a percentage was calculated representing the likelihood that muscle hypertrophy was highest or among the highest relative to other categories. Where applicable, we reported probabilities as *p*-values representing the proportion of the distribution that exceeded zero.

Informative priors were used for all models. For the hierarchical meta-regressions, the mean pre to post intervention change included an informative prior obtained from a large meta-analysis of strength and conditioning outcomes expressed in terms of SMDs (22). For controlled effect sizes, similar research in strength and conditioning conducted with comparative effect sizes was used (25). For the between-studies standard deviation, informative priors were based on an analysis of the predictive distributions generated from a large number of previous meta-analyses (26). It is a common limitation in meta-analyses using SMDs from intervention change scores to use a fixed value for the pre- to post-study correlation (e.g., a value of 0.7) not based on any empirical data (27). To account for this limitation, the sampling error for each study was estimated using an informative uniform prior with lower bound based on the sampling error calculated with a correlation of 0.9 and the upper bound based on the sampling error calculated with a correlation of 0.5. All analyses were performed in R, using the R2OpenBUGS package (28) for Bayesian sampling.

To improve accuracy, transparency and replication in the analyses, the WAMBS-checklist (When to worry and how to Avoid Misuse of Bayesian Statistics) was used and incorporated sensitivity analyses that included non-informative priors (29). Documentation for the WAMBS-checklist is provided in the supplementary files along with other diagnostics for primary analyses (including funnel plot and transitivity check for distribution of study characteristics across treatment comparisons in network). Consistency analyses were not conducted on networks due to insufficient data and a lack of loops in the networks.

Results

We initially screened 359 studies and identified 11 that potentially met inclusion criteria. After reviewing the full texts of these studies, 2 studies were excluded: one because neither set volume nor volume load was equated between conditions (30) and the other because the loading range was not equated in the initial set of the given exercise(s) (31). Figure 1 provides a flow chart of the search process.

Study characteristics

Eight studies employed young participants (18–35 years of age) (32–39) and 1 employed older participants (>65 years of age) (40). Six studies employed untrained participants (32–36, 40) and 3 studies employed resistance-trained participants (37–39). Six studies employed male participants (32, 33, 37–40), 1 study employed female participants (36), 1 study employed both male and female participants (35), and 1 study did not specify the sex of participants (34). Three studies assessed total body measures of hypertrophy (32, 33, 40), 5 studies assessed upper body measures of hypertrophy (biceps brachii and triceps brachii) (33, 34, 37–39), and 7 studies assessed lower body measures of hypertrophy (quadriceps femoris and total thigh) (33–39). The duration of the included studies ranged from 5 to 10 weeks. Table 1 provides a descriptive overview of each study's methodological design.

Meta-analysis of non-controlled effect sizes

Meta-analyses on non-controlled effect sizes using hierarchical models of all 19 measurements (thigh: 10; arm: 6; whole body: 3) from nine studies are presented in Figures 2, 3. Both meta-analyses showed substantial overlap of SMDs across the different inter-set rest periods [Binary: short: 0.48 (95%CrI: 0.19–0.81), longer: 0.56 (95%CrI: 0.24–0.86); Four categories: short: 0.47 (95%CrI: 0.19–0.80), intermediate: 0.65 (95%CrI: 0.18–1.1), long: 0.55 (95%CrI: 0.15–0.90), very long: 0.50 (95%CrI: 0.14–0.89)], with substantial heterogeneity in results. Central estimates suggested that improvements across the interventions were most likely to be between medium and large, highlighting that interventions included in this review were generally effective irrespective of rest interval duration.

Meta-analysis of controlled effect sizes

Univariate and multivariate meta-analyses of controlled binary (short vs. longer) effect sizes were conducted for outcomes separated by body region (arm, thigh, whole body; Figures 4–6). Similar results were obtained for the arm and thigh with central estimates slightly favoring longer rest periods [arm: 0.13 (95%CrI: −0.27 to 0.51); τ: 0.10 (75%CrI: 0.02–0.31), Figure 4; thigh: 0.17 (95%CrI: −0.13 to 0.43); τ: 0.17 (75%CrI: 0.02–0.22), Figure 5]. In contrast, central estimates closer to zero but slightly favoring shorter rest periods were estimated for the whole body [whole body: −0.08 (95%CrI: −0.45 to 0.29); τ: 0.08 (75%CrI: 0.02–0.27), Figure 6]. Application of the multivariate meta-analysis model resulted in slight reductions in uncertainty with smaller central estimates all modestly favoring longer rest periods [arm: 0.11 (95%CrI: −0.26 to 0.48); thigh: 0.16 (95%CrI: −0.13 to 0.41); whole body: 0.03 (95%CrI: −0.28 to 0.36)].

Controlled effect sizes for the four categories of inter-set rest period were analyzed with network meta-analyses. Sufficient data were available for univariate analysis of the arm and thigh. Network structures are presented in the supplementary files, with effect size estimates combining direct and indirect estimates, and SUCRA values presented in Table 2. In general,

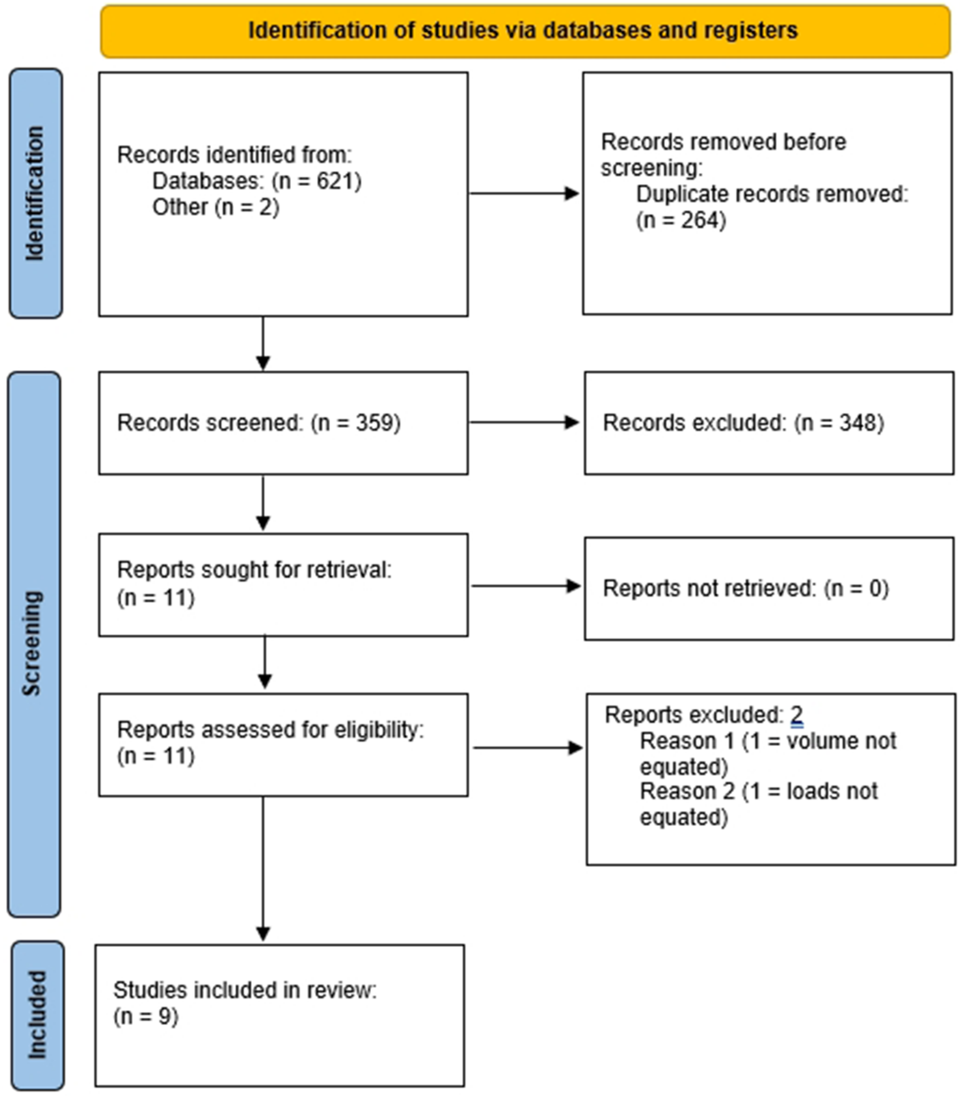

FIGURE 1
PRISMA flow chart of the search process.

effect size estimates and SUCRA values for both regions of the body indicated greater effectiveness for rest periods beyond the short categorization. In general, effect size estimates and SUCRA values ranking rest periods indicated greater effectiveness for durations beyond the short categorization in both regions of the body.

Subanalyses

Subanalyses were performed on direct comparisons of binary effect sizes separating studies based on set end-point (i.e., training to momentary muscular failure or non-failure) and training status (specific to designs that included untrained participants). A multivariate analysis comprised of data from three studies that incorporated training to momentary muscular failure was conducted for hypertrophy of the thigh [0.31 (95% CrI: −0.03 to 0.61)] and arm [0.04 (95%CrI: −0.37 to 0.44)]. Similarly, a multivariate analysis comprised of data from three studies that incorporated non-failure RT was conducted for hypertrophy of the thigh [0.27 (95%CrI: −0.02 to 0.51)] arm [0.04 (95%CrI: −0.37 to 0.44)], and whole body [−0.06 (−0.40 to 0.27)]. Consistency in results provided no evidence of a difference in the influence of rest periods for different set end-points. Finally, sufficient data were available to perform a multivariate analysis comprised of data from six studies that included untrained participants and was conducted for hypertrophy of the thigh [0.17 (95%CrI: −0.15 to 0.47)] arm [0.02 (95%CrI: −0.41 to 0.46)], and whole body [−0.05 (−0.43 to 0.26)]. Insufficient data were available to subanalyze results in trained individuals.

Below is a funnel plot that illustrates calculated effect sizes from binary categorisation (shorter versuslonger rest periods) for muscular hypertrophy measured at the arms (upper), thighs

TABLE 1 Summary of the methods of included studies.

Study	Sample	Design	Exercises	RT protocol	Hypertrophy measure	Duration
Buresh et al. (33)	12 young, untrained men	Parallel group random assignment to 1 of 2 groups: (1) 60 s RI; (2) 150 s RI	Squat, leg curl, leg extensions, standing heel raise, seated dumbbell press, dumbbell lateral raises, rear delts on pec-deck, abdominal crunches, lying leg raises, pull-downs, machine rows, machine bench press, pec flies, incline dumbbell curls, machine biceps curls, dumbbell kickbacks	TB protocol performed 2 d/wk consisting of 2–3 sets of 10 repetitions per exercise	- Hydrodensitometry: FFM - Skinfold and CIR: CSA of arm and thigh	10 wks
de Souza et al. (37)	20 young, resistance-trained men	Parallel group random assignment to 1 of 2 groups: (1) 120 s RI; (2) RI decreasing from 120 s to 30 s (mean RI = ~80 s)	Bench press, incline bench press, wide grip lat pulldown, leg extension, leg curl machine, front military press, dumbbell shoulder lateral raises, barbell curls, triceps pushdown, barbell lying triceps extension, abdominal crunches	TB protocol performed 6 d/wk consisting of 3–4 sets of 8–12 repetitions per exercise	- MRI: CSA of arm and thigh	8 wks
Fink et al. (31)	21 young, untrained individuals	Parallel group random assignment to 1 of 2 groups: (1) 30 s RI; (2) 150 s RI	Barbell curl, preacher curl, hammer curl, close grip bench press, French press, dumbbell extension	4 sets of squats and bench performed 2 d/wk at 40% 1RM	- MRI: CSA of triceps brachii and thigh	8 wks
Hill-Haas et al. (36)	18 young, untrained women	Parallel group random assignment to 1 of 2 groups: (1) 20 s RI; (2) 80 s RI	Parallel squats, bench step-ups with dumbbells, leg press (seated), dumbbell lunge, knee extensions, leg curls, bench press, seated rows, lat pull downs, dumbbell shoulder press. abdominal crunches	TB protocol performed 3 d/wk consisting of 2–5 sets of 15–20 repetitions per exercise	- CIR: thigh	5 wks
Longo et al. (35)	28 young, untrained men and women	Within-participant random assignment of legs to 1 of 4 conditions: (1) 60 s RI; (2) 180 s RI; (3) 60 s RI with VL equated to long RI; (4) 180 s RI with VL equated to short RI	Unilateral inclined leg press	3 sets of leg press performed 2 d/wk at 80% 1RM	- MRI: CSA of quadriceps femoris	10 wks
Piirainen et al. (32)	21 young, untrained men	Parallel group random assignment to 1 of 2 groups: (1) 55 s RI; (2) 120 s RI	Leg press, plantar flexion, bench press, elbow extension, shoulder press, low back, abdominal, knee extension, knee flexion, rowing, cable pulldown, upright row, back, trunk rotation	TB protocol performed 3 d/wk consisting of 3 sets of 10–20 repetitions per exercise	- BIA: FFM	7 wks
Schoenfeld et al. (39)	21 young, resistance-trained men	Parallel group random assignment to 1 of 2 groups: (1) 60 s RI; (2) 180 s RI	Barbell back squat, plate-loaded leg press, plate-loaded leg extension, flat barbell press, seated barbell military press, wide-grip plate-loaded lateral pulldown, plate-loaded seated cable row	TB protocol performed 3 d/wk consisting of 3 sets of 8–12 repetitions per exercise	- US: MT of biceps brachii, triceps brachii, quadriceps femoris	8 wks
Souza-Junior et al. (38)	22 young, resistance-trained men	Parallel group random assignment to 1 of 2 groups: (1) 120 s RI; (2) RI decreasing from 120 s to 30 s (mean RI = ~80 s)	Bench press, incline bench press, wide grip lat pulldown, machine seated row, back squat, leg extension, leg curl machine, front military press, dumbbell shoulder lateral raises, barbell curls, alternating biceps curl with dumbbells, triceps pushdown, barbell lying triceps extension, abdominal crunches	TB protocol performed 6 d/wk consisting of 3–4 sets of 8–12 repetitions per exercise	- MRI: CSA of upper arm and thigh	8 wks
Villanueva et al. (40)	22 older, untrained men	Parallel group random assignment to 1 of 2 groups: (1) 60 s RI; (2) 240 s RI	45° bilateral leg press, flat bench machine chest press, lat pulldown, seated row, dumbbell step-ups, dumbbell Romanian deadlifts, bilateral knee extension/flexion	TB protocol performed 3 d/wk consisting of 2–3 sets of 4–6 repetitions per exercise	- DXA: FFM	8 wks

RI, rest interval; TB, total body; VL, volume load; FFM, fat-free mass; MT, muscle thickness; CIR, circumference; US, ultrasound; VM, vastus medialis; DXA, dual-energy x-ray absorptiometry; MRI, magnetic resonance imaging; BIA, bioelectrical impedance analysis.

(lower) and whole body. Data points are clustered around the central pooled estimate (vertical line) and its 95% credible interval (rectangular shaded region). Plot illustrates no concern with small-study effects.

Analyses of small study bias

Visual inspection of the funnel plot indicates no evidence of small study bias (see supplemental file).

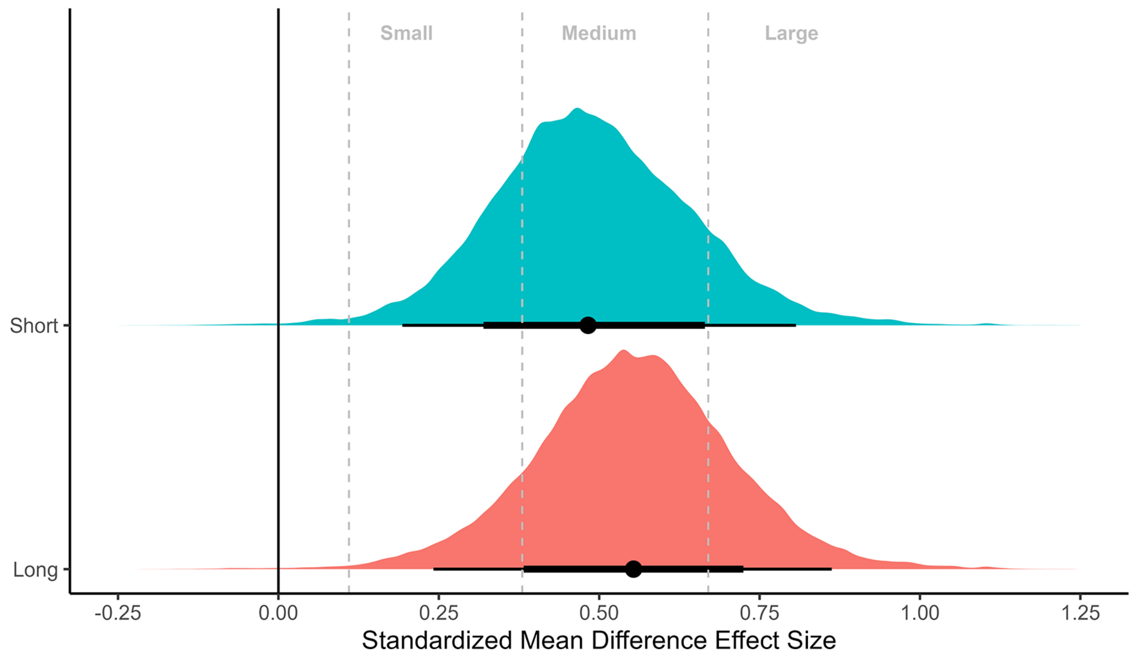

FIGURE 2
Meta-analysis of non-controlled effect sizes separated by binary categorization of short (≤60 s) vs. long (>60 s) inter-set rest periods. Plots illustrate shrunken posterior distribution of effect sizes following application of meta-analytic model. Circle: median, error bars represent 75 and 95% credible intervals. Small, medium, and large effect size thresholds are presented according to previous research in strength and conditioning (22).

Methodological qualitative assessment

Qualitative assessment of included studies via the SMART-LD tool showed a mean score of 15 out of a possible 20 points (range: 12–17 points). Four studies were judged to be of good quality (34, 37, 38, 40), 4 studies were judged to be of fair quality (32, 35, 36, 39), and 1 study was judged to be of poor quality (33), see supplementary files.

Discussion

Our meta-analysis quantified data from studies that directly compared the effects of different rest interval lengths on measures of muscle hypertrophy. While the initial meta-regressions with non-controlled effect sizes highlighted substantial heterogeneity across studies (Figures 2, 3), they also demonstrated that most interventions were effective in eliciting hypertrophic adaptations regardless of rest interval duration, with SMDs that could be considered medium to large in magnitude. Binary categorization comparing short (≤60 s) with longer (>60 s) rest intervals returned slightly greater central estimates favoring the longer rest condition (SMD = 0.56 vs. 0.48, respectively; Figure 2). When further stratifying data, results showed slight differences between short (SMD = 0.47), intermediate (SMD = 0.65), long (SMD = 0.55) and very long (SMD = 0.50) rest periods (Figure 3). These results suggest no clear benefit to altering rest interval length for the purpose of promoting muscle hypertrophy. However, given substantial heterogeneity, meta-regressions with a small number of studies provide limited ability to draw strong inferences as any differences observed can be the result of chance imbalances in the distribution of studies. Therefore, the primary inference from this study was focused on meta-analyses that comprised controlled effect sizes with either direct pairwise comparisons only (bivariate categorization), or both direct and indirect pairwise comparisons (four categories) through network models.

Meta-analyses were conducted within a Bayesian framework as is most common with network models to naturally produce ranking and probability outputs to better interpret results (41). Additionally, Bayesian models allow for the use of informative priors which were placed here on the sampling error of effect sizes, the between study variation, and the effect size values using previous knowledge to enhance precision of estimates.

Sub-analysis of body regions

When subanalyzing the effects of rest interval length on hypertrophy of the upper and lower limbs, the results suggest a small benefit for rest intervals >60 s. For the binary categorization, the pooled effect size for the arms slightly favored a hypertrophic benefit for longer vs. shorter rest durations (SMD = 0.13). The probability of the effect being greater than zero was 74%, with only a 45% probability that the difference in effect was greater than small. Similarly, the pooled effect size for quadriceps femoris modestly favored longer vs. shorter durations (SMD = 0.17). There was a strong probability that this effect was greater than zero (88%), but only a 54% probability that the difference in effect was

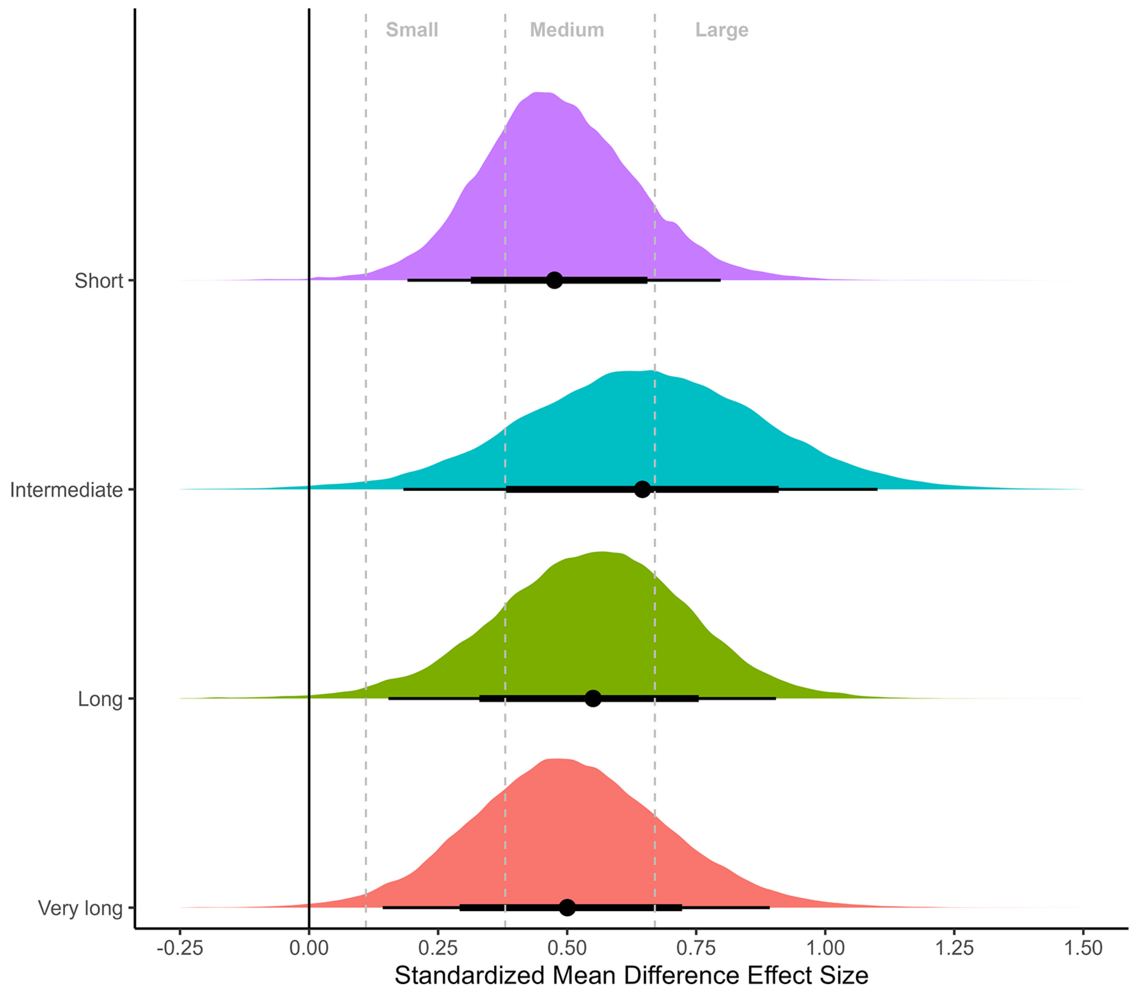

FIGURE 3
Meta-analysis of non-controlled effect sizes separated by short (≤60 s), intermediate (61 s–119 s), long (120–179 s), and very long (≥180 s) categorization of inter-set rest period. Plots illustrate shrunken posterior distribution of effect sizes following application of meta-analytic model. Circle: median, error bars represent 75 and 95% credible intervals. Small, medium, and large effect size thresholds are presented according to previous research in strength and conditioning (22).

greater than small. Both upper and lower limb analyses showed a very low probability that differences would be greater than a medium effect (SMD = 0.18 and 0.15, respectively). Conversely, measures of whole-body hypertrophy showed slightly greater effects favoring shorter vs. longer rest durations (SMD = −0.08, p (>0) = 0.69, p (>small) = 0.36); however, with substantial uncertainty due to only three studies providing whole body data.

Potential discrepancies between findings of hypertrophy of the extremities vs. the whole body may be related to the different methods of assessment. Whole-body measures of muscle growth were based on estimates of fat-free mass (FFM) via DXA, BIA and hydrodensitometry, which are often used as proxies for muscle hypertrophy (42). However, FFM encompasses all bodily tissues other than fat mass; while alterations in skeletal muscle comprise the majority of FFM changes that occur during RT, other components such as water and mineral can influence results as well (43). Alternatively, the majority of assessments for the extremities employed direct measurements of changes in muscle mass via MRI and ultrasonography. Given that direct assessment methods have been shown to be more sensitive to detecting RT-induced hypertrophy than indirect assessments (44, 45), the results of our whole-body analysis should be interpreted with caution.

Rest interval duration and volume load

Potential beneficial effects of rest periods greater than 60 s on muscle hypertrophy may be attributable to preservation of volume load during a training session. Research indicates that short rest periods (≤60 s) appreciably reduce the number of repetitions performed across multiple sets compared to longer rest durations (11, 12, 46), which could have a detrimental effect on long-term muscular adaptations. This hypothesis is supported by Longo et al. (35), who reported appreciably greater increases in quadriceps femoris cross-sectional area when training with 180 vs. 60 inter-set rest periods over a 10-week intervention (13.1% vs. 6.8%,

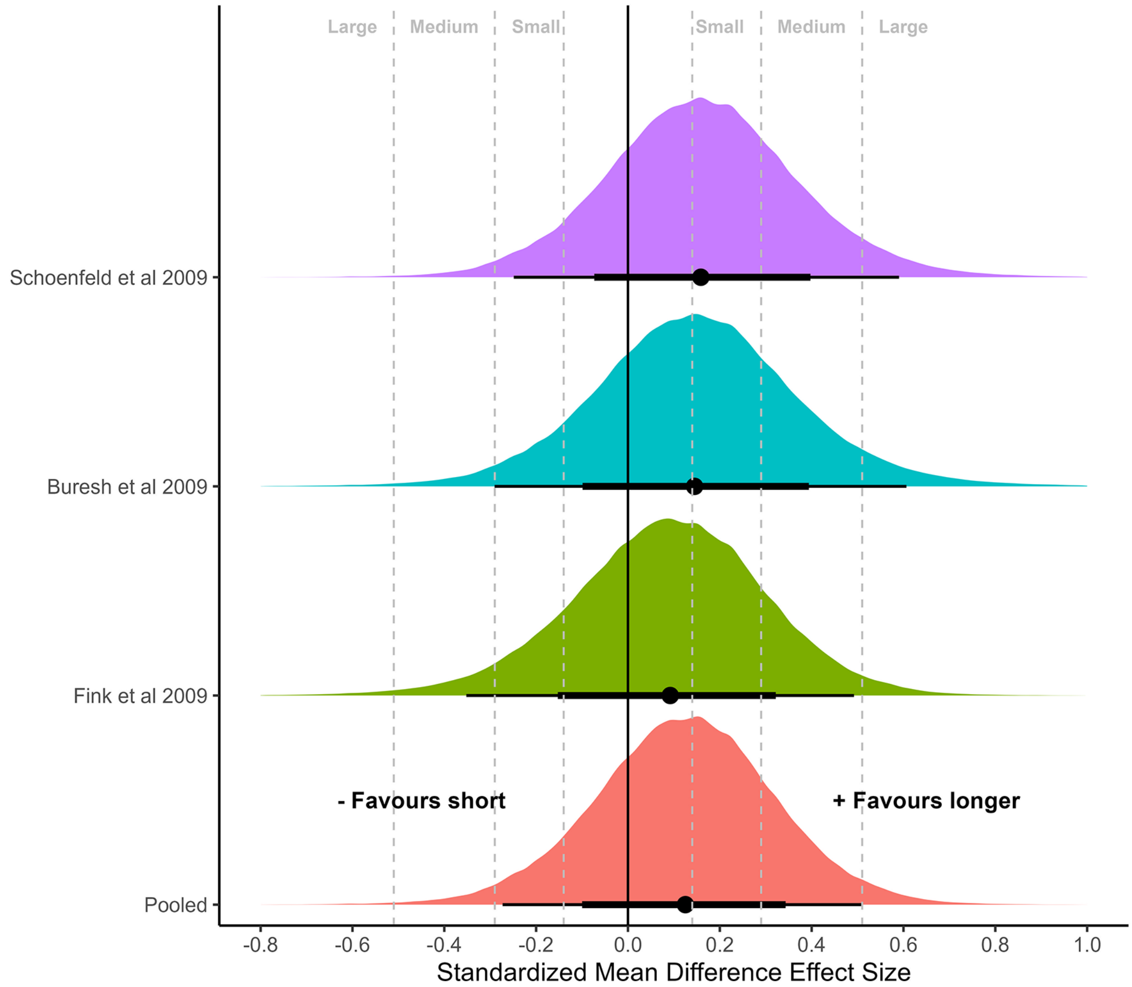

FIGURE 4
Meta-analysis of controlled effect sizes of muscular hypertrophy of the upper arm with direct comparisons of binary categorization of inter-set rest period. Plots illustrate shrunken posterior distribution of effect sizes following application of meta-analytic model. Circle: median, error bars represent 75 and 95% credible intervals. Small, medium, and large effect size thresholds are presented according to previous research in strength and conditioning (25). Probability of effect size greater than 0 favoring longer rest period = 0.74; probability of effect size greater than small favoring longer rest period = 0.45; probability of effect size greater than medium favoring longer rest period = 0.18; probability of effect size greater than large favoring longer rest period = 0.03.

respectively); of note, volume load was reduced to a significantly greater extent in the shorter vs. longer rest condition (average number of repetitions across 3 sets: 9.8 ± 2.9 vs. 16.1 ± 5.2, respectively). However, similar hypertrophy was observed with the performance of additional sets to equate volume load between conditions.

Alternatively, previous evidence suggests that differences in volume load tend to level off when comparing rest intervals of 120 vs. 180 s (11, 46). When compared to very short rest intervals (≤60 s), our network meta-analysis suggested that very long rest intervals (≥180 s) provided a modest advantage vs. intermediate (61–119 s) and long (120–179 s) durations with respect to quadriceps femoris hypertrophy. However, these data showed a high degree of uncertainty and the U-shaped response in the median estimates between conditions casts further doubt on the veracity of the finding. Analyses of arm hypertrophy did not show an appreciable effect of rest interval durations beyond intermediate (>60 s) durations. Future research should explore this topic in greater detail to better determine whether graded increases in rest interval durations alter muscular adaptations as well as the extent to which volume load may play a role in the process.

Sub-analysis of proximity-to-failure

Subanalysis of set end-point found that the proximity-to-failure of set termination (i.e., failure or non-failure) did not meaningfully influence the interaction between rest interval duration and muscle hypertrophy. Central estimates from both analyses suggested a hypertrophic benefit for longer rest periods in the quadriceps femoris, irrespective of the proximity-to-failure reached during RT. However, the magnitude of effect was relatively small (SMD = 0.27 and 0.31 for non-failure and failure conditions, respectively). Alternatively, negligible differences were observed for the influence of rest interval length in the arms

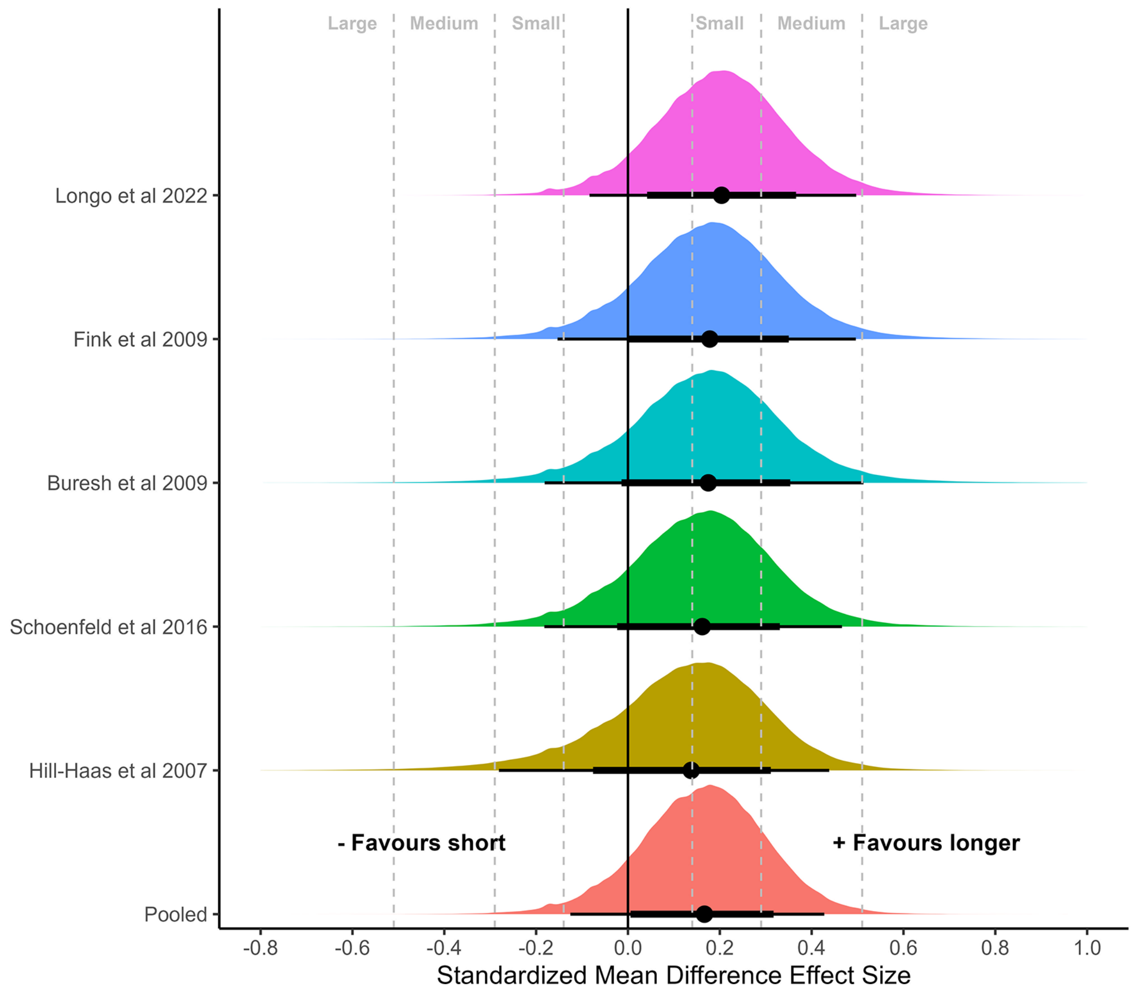

FIGURE 5
Meta-analysis of controlled effect sizes of muscular hypertrophy of the thigh with direct comparisons of binary categorization of inter-set rest period. Plots illustrate shrunken posterior distribution of effect sizes following application of meta-analytic model. Circle: median, error bars represent 75 and 95% credible intervals. Small, medium, and large effect size thresholds are presented according to previous research in strength and conditioning (25). Probability of effect size greater than 0 favoring longer rest period = 0.88; probability of effect size greater than small favoring longer rest period = 0.54; probability of effect size greater than medium favoring longer rest period = 0.15; probability of effect size greater than large favoring longer rest period = 0.01.

(SMD = 0.04) regardless of proximity-to-failure. The findings are somewhat in contrast with data showing that shorter rest periods impair bench press performance to a greater extent than longer rest periods when training with closer proximities to failure (47). Further research is needed to better understand the potential discrepancies between acute and longitudinal outcomes.

Sub-analysis of participant training status

Subanalysis of the potential influence of training status on rest interval length showed that untrained individuals displayed a slight hypertrophic benefit from longer rest periods when training the quadriceps femoris (SMD = 0.17). However, rest interval length appeared to have negligible effects on measures of arm and whole-body hypertrophy in untrained individuals (SMD = 0.02 and −0.05, respectively). These data are relatively consistent with findings from a systematic review by Grgic et al. (15) that concluded both shorter and longer rest durations are equally viable options for promoting hypertrophy in novice trainees. The systematic review by Grgic et al. (15) also suggested that trained individuals might benefit from the use of longer rest intervals, conceivably by allowing for a greater volume load across multi-set protocols. Unfortunately, there was insufficient data to subanalyze results on trained lifters, precluding our ability to further generalize this claim. Further research is therefore needed to better understand how training status may influence the response to rest interval length.

Limitations

Our analysis has several limitations that should be considered when drawing practical inferences for exercise prescription. First,

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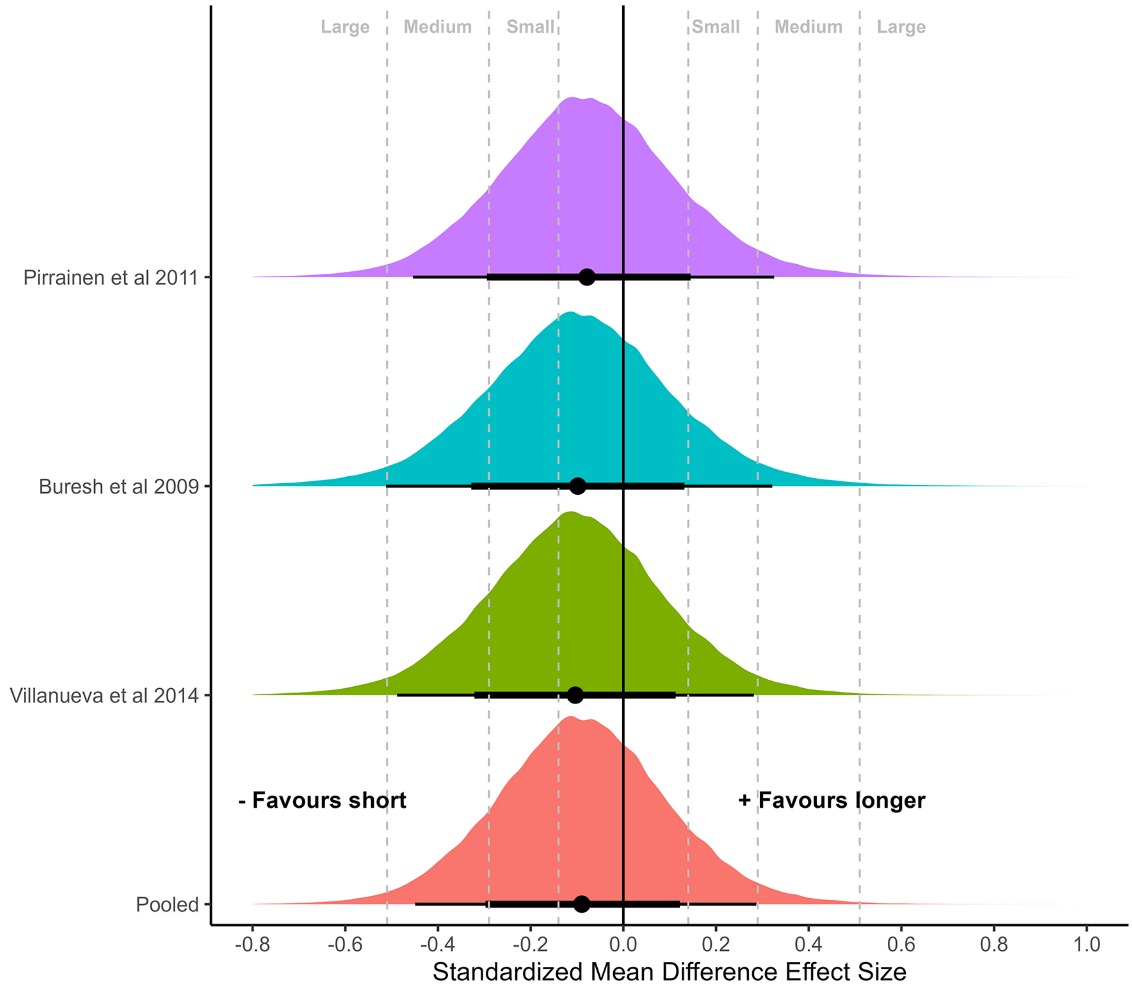

FIGURE 6
Meta-analysis of controlled effect sizes of muscular hypertrophy of the whole body with direct comparisons of binary categorization of inter-set rest period. Plots illustrate shrunken posterior distribution of effect sizes following application of meta-analytic model. Circle: median, error bars represent 75 and 95% credible intervals. Small, medium, and large effect size thresholds are presented according to previous research in strength and conditioning (25). Probability of effect size greater than 0 favoring short rest period = 0.69; probability of effect size greater than small favoring short rest period = 0.36; probability of effect size greater than medium favoring short rest period = 0.12; probability of effect size greater than large favoring short rest period = 0.01.

TABLE 2 Univariate network meta-analyses combining direct and indirect pairwise comparisons for hypertrophy at the thigh and arm for the four inter-set rest period categories.

Region	Category	Comparative effect size (95%CrI)	SUCRA
Arm	Short	–	0.40
	Intermediate	0.22 (−0.31 to 0.74)	0.49
	Long	−0.02 (−0.43 to 0.37)	0.52
	Very long	0.18 (−0.36 to 0.70)	0.60
Thigh	Short	–	0.18
	Intermediate	0.13 (−0.31 to 0.58)	0.54
	Long	0.01 (−0.39 to 0.41)	0.63
	Very long	0.32 (−0.10 to 0.68)	0.64

Comparative effect sizes are expressed relative to the short inter-set rest category. CrI, Credible interval; SUCRA, Surface Under the Cumulative Ranking curve.

the included studies had substantial heterogeneity in exercise selection, with the protocols employing varying use of free weights and machines as well single-joint and multi-joint movements (and, in some cases, combinations of these modes). Given that the complexity of an exercise may alter the fatigue response across sets (11), it is conceivable that rest interval prescription should vary based on the type of exercise employed. Second, no studies have investigated the effect of rest interval length on the muscles of the torso (i.e., pectorals, latissimus dorsi, deltoids etc); it is possible that these muscle groups may respond differently to shorter rest durations than those of the limbs, although this seems unlikely. Third, the volume of training was generally moderate for the included studies; therefore, it remains undetermined how differences in rest interval length might influence hypertrophy with a higher number of sets performed per muscle group. Fourth, the majority of studies to date have been carried out on untrained, younger participants. Further study is therefore warranted in resistance-trained individuals and older adults to better generalize findings to this population. Finally, while the observed differences in effect are likely to be between zero and small, intervention durations were relatively short (between 5 and 10 weeks); thus, it is possible that accumulated differences in muscle mass accretion may be more appreciable over longer time frames.

Conclusion

This meta-analysis indicates that hypertrophy can be achieved across a wide spectrum of rest interval ranges but suggests a small benefit to employing longer vs. shorter inter-set rest intervals for muscle hypertrophy. The effect favoring longer inter-set rest intervals was relatively consistent between the arms and the legs musculature, and results were not meaningfully influenced by whether RT was performed to failure or non-failure. These findings are inconsistent with recommendations from the National Strength and Conditioning Association, which prescribe relatively short rest periods (30–90 s) for hypertrophy-related goals (7). Thus, current guidelines regarding rest interval prescription for achieving muscular hypertrophy warrant reconsideration.

The current evidence remains equivocal as to whether resting more than 90 s between sets further enhances hypertrophic adaptations. Our analysis casts doubt as to any beneficial effects in this regard. However, given the uncertainty of evidence, additional studies are needed comparing measures of hypertrophy across a wide spectrum of rest periods to provide better insights on the topic.

Data availability statement

Data and supplementary material are available on the Open Science Framework project page: https://osf.io/zp6vs/.

Author contributions

AS: Writing – original draft, Writing – review & editing. MW: Writing – original draft, Writing – review & editing. LG: Writing – original draft, Writing – review & editing. EA: Writing – original draft, Writing – review & editing. KD: Writing – original draft, Writing – review & editing. EE: Writing – original draft, Writing – review & editing. AM: Writing – original draft, Writing – review & editing. PA: Writing – original draft, Writing – review & editing. MR: Writing – original draft, Writing – review & editing. PS: Writing – original draft, Writing – review & editing. BS: Writing – original draft, Writing – review & editing.

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Conflict of interest

BJS formerly served on the scientific advisory board for Tonal Corporation, a manufacturer of fitness equipment.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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The effect of optimal load training on punching ability in elite female boxers

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Optimal load training is a method of training that aims to maximize power output. This is achieved by arranging optimal loads (optimal ratios of load intensity and load volume) during strength training. The fixed load intensity and number of repetitions employed in traditional strength training. The present study will investigate the applicability of these two load arrangements to female elite boxers. Twenty-four elite female boxers were divided into three groups [optimal load (OL = 8), traditional load (TL = 8) and control group (CG = 8)]. The six-week intervention consisted of strength training with different loading arrangements. The punching ability and strength were tested before and after the intervention. We found that optimal load training enhances a boxer's punching ability and economy, which aligns with the demands of boxing and is suitable for high-level athletes, whose strength training loads require a more individualised and targeted approach.

KEYWORDS

boxing, punching ability, optimal load training, strength training, training load

1 Introduction

In amateur women's boxing, the significant time structure characteristics and intense confrontation make it a high-intensity sport. Athletes must complete a large number of short, high-explosive movements during the whole match (Three rounds of 3 min each, with a one-min break between rounds). As the rules of boxing have changed and the emphasis on physical fitness has increased in recent years, the style of boxing has shifted from point scoring to intense confrontation. This necessitates that athletes possess highly developed muscular strength and explosive power in order to enhance their punching ability, thereby creating a deterrent to gain an advantage in the game (Piorkowski et al., 2011). Consequently, the current focus of research is on the maximisation of the punching force, punching speed and punching power of boxers, with the objective of improving the punching ability and guaranteeing the effective punching.

Strength is the maximal force a muscle or muscle group can generate against resistance (Marzuca-Nassr et al., 2024). Force is an interaction that changes the motion of an object when unopposed (Olberding and Deban, 2017). Power is the rate at which work is done or energy is transferred (Cormie et al., 2010). Velocity is the rate of change of an object's position, including direction and magnitude (Horan and Kavanagh, 2012). Speed is how fast an object is moving, measured as distance traveled per unit time (Horan and Kavanagh, 2012). Strength is regarded as the cornerstone of boxers' confrontation ability, and power output is the embodiment of strength. Athletes' maximal power output ability is regarded as one of the key factors to win the game (Turner et al., 2011). The successful implementation of techniques and tactics in most sports is based on the athletes' ability to achieve maximal

TABLE 1 Basic information sheet for subjects.

	OL	TL	CG
Height (cm)	166.21 ± 3.14	166.13 ± 2.87	167.16 ± 2.74
Weight (kg)	64.67 ± 11.54	62.65 ± 11.94	63.39 ± 14.04
Age (year)	22.4 ± 1.65	22.38 ± 1.58	22.44 ± 1.55
BP (kg)	56.88 ± 5.56	56.88 ± 4.28	56.56 ± 2.48
SQ (kg)	63.13 ± 4.96	61.88 ± 4.28	66.25 ± 4.44

power output. Furthermore, the power output ability is closely related to the athletic performance. In order to ensure the safety and effectiveness of training, especially for elite athletes, the training load arrangement should be more accurate and targeted based on the consideration of individual differences (Soriano et al., 2015). Therefore, it is important to have a deep understanding of the interrelationship between training variables, including load intensity and load volume, interval time, movement pattern and movement speed, and so forth. A number of studies have demonstrated that the most effective training outcomes are achieved through the utilisation of load arrangements that maximise power output during training, and are therefore defined as optimal training loads (Kawamori and Haff, 2004; Peterson et al., 2004). Training with individual optimal loads represents a strength training method that seeks to optimise the combination of force and speed. This method has been demonstrated to have significant training effects in sports that require explosive movements (Cormie et al., 2011a; Flores et al., 2017). The objective of strength training for boxers is not merely to enhance muscular strength, rather, it is to facilitate the transfer of strength gains from training to improved punching ability (Loturco et al., 2021).

In this study, optimal load training is defined as the optimal ratio of load intensity and load volume that results in the greatest possible power output (Loturco et al., 2017). The monitoring tool used was the GymAware PowerTool system (GYM). Therefore, this study investigated the effects of a 6-week training intervention on the punching ability and strength of elite female boxers by designing a training intervention programme with two different loading regimens (optimal load training and traditional load training) and a control group (performing conventional training).

We hypothesize that following a six-week intervention period, the three subject groups would demonstrate targeted improvements in punching ability and strength. It was further hypothesised that optimal loading training would prove more applicable to boxing and may benefit punching ability, whereas traditional loading training may focus on strength gains.

2 Materials and methods

2.1 Sample and participants

Twenty-four elite female boxers (age 22.12 ± 2.84 years; height 165.52 ± 4.67 cm; weight 64.56 ± 12.17 kg) were randomly assigned to three groups [optimal load (OL = 8), traditional load (TL = 8) and control group (CG = 8)], specific information is provided in Table 1. Participants reported no history of injury or illness in the 6 months prior to the experiment. They were informed about the procedure and the aim of the study, and subsequently they provided their written consent for participation. Ethical consent was provided by Shanghai University of Sport research ethics committee (approval number: 102772023RT153) and in accordance with the Helsinki declaration.

2.2 The main experimental steps

The whole experiment was divided into four parts: pre-test, intervention load test, 6-week intervention and post-test. In this study, the athlete's punching ability was measured by Strike Tec Boxingperformance Tracking (STRIKETEC SENSOR KIT), the GYM is used to test the power output when performing training maneuvers, and the CMJ test used the Smart jump electronic long jump pad for testing.

The optimal training load intensity for the upper and lower limbs of the OL was derived through the intervention load test. This required the subjects to start at a load intensity of 30% 1 RM and complete the test movement three times in a row, with the data recorded through the real-time feedback data from the GYM. This enabled the calculation of the average power, average propulsive power, and peak power of the three movements. Following the completion of the 30% 1 RM load intensity test movement, the subject was required to rest for a period of 5 min before commencing the 40% 1 RM load intensity test. This involved the completion of three consecutive movements, with a further 5 min of rest between each set. The load intensity was increased by 10% 1 RM each time, up to a maximum of 70% 1 RM. During the test, when a significant decrease in average power, average propulsive power, and peak power was observed to be lower than that of the previous set, the test was concluded, and the load that was able to produce the maximum power output was regarded as the optimal load and used as the intervention load (Loturco et al., 2013; Cormie et al., 2011b).

The training intervention comprised a series of exercises, including squats, bench presses, bench pulls and hip thrusts. The load intensity of the OL was the optimal load that could achieve the maximum power output derived from the pre-intervention load test. The load volume was preset to 4-9 repetitions, and the whole process was monitored in real time by the GYM. When the power output decreased significantly, the training of the group ended and entered into a 20 s break between sets. TL are loaded at 61%–66% 1 RM and loaded at 50% of the maximum number of repetitions at that loaded intensity (Sarabia et al., 2017). The OL and TL are completed with six sets of each movement, with a 20-s rest period between sets and a 2–5 min rest period between each training movement (Baker, 2003). The CG underwent routine training.

Outcome measures were: 1) Punching ability: single punching force (SPF), single punching speed (SPS), single punching power (SPP); Average force of continuous punching (CPF), average speed of continuous punching (CPS), average power of continuous punching (CPP); Number of sandbags punch in 10 s (10 PS), Number of sandbags punch in 30 s (30 PS), Number of sandbags punch in 60 s (60 PS) (Smith et al., 2000). 2) Strength: 1 RM bench press (BP), 1 RM squat (SQ), counter movement jump (CMJ).

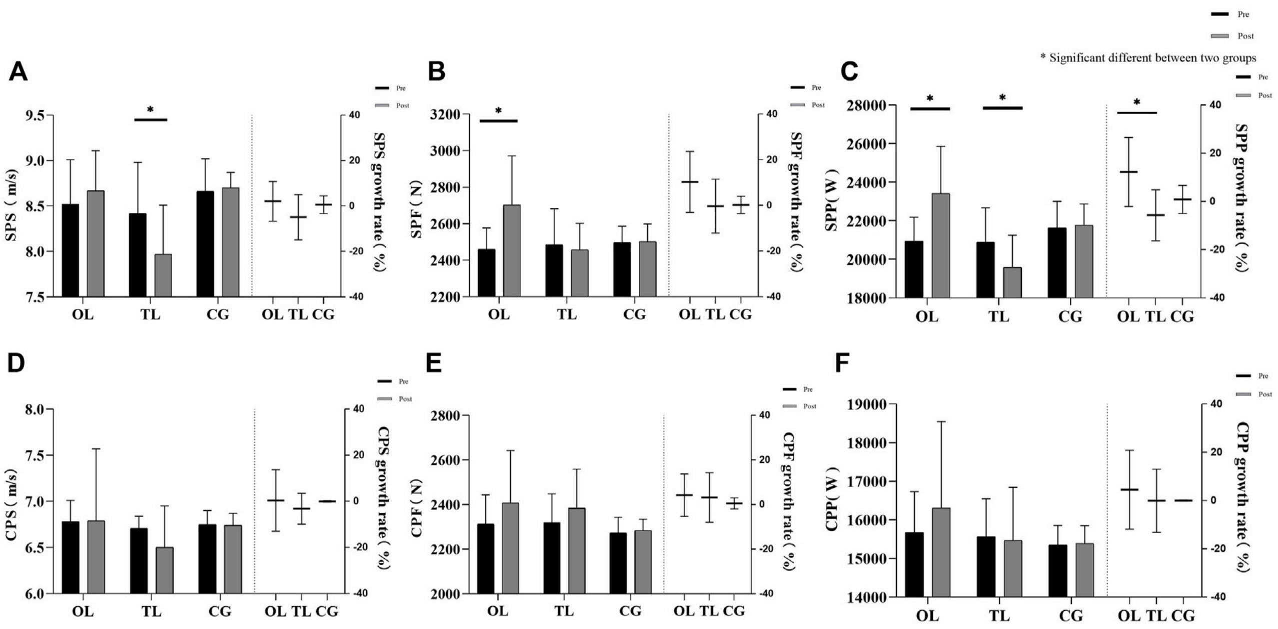

FIGURE 1
Results of one-way repeated-measures analysis of variance for punching ability: **(A)** single punching speed (SPS), **(B)** single punching force (SPF), **(C)** single punching power (SPP), **(D)** average speed of continuous punching (CPS), **(E)** average force of continuous punching (CPF), **(F)** average power of continuous punching (CPP).

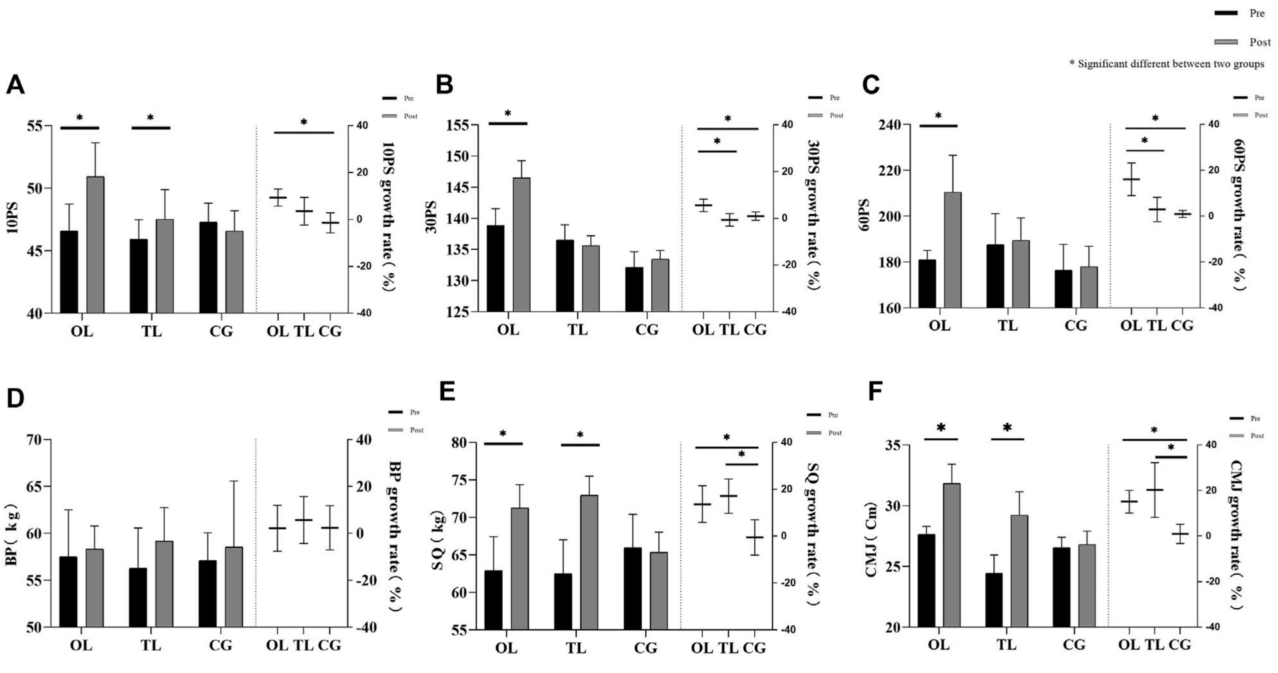

FIGURE 2
Results of one-way repeated-measures analysis of variance for sandbags punch and strength test: **(A)** number of sandbags punch in 10 s (10 PS), **(B)** number of sandbags punch in 30 s (30 PS), **(C)** number of sandbags punch in 60 s (60 PS), **(D)** 1 RM bench press (BP), **(E)** 1 RM squat (SQ), **(F)** counter movement jump (CMJ).

2.3 Statistical analysis

Statistical analyses were conducted with IBM statistics SPSS v26.0 software (SPSS Inc., Chicago, IL, United States). A Shapiro-Wilk test was initially used to assess the normal distribution of the data, which was found to be satisfactory. One-way ANOVA was used to analyze the physical characteristics of the participants across the three groups in terms of age, height, weight BP and SQ. A two-way repeated-measures ANOVA with a Bonferroni *post hoc* test was used to detect significant differences within groups between week 0 and week 6 of training. Differences in improvement effect by group were tested by the one-way repeated-measures analysis of variance with a Bonferroni *post hoc* test. Growth rate = (post-test - pre-test)/ pre-test * 100%.

Utilizing G*Power 3.1 software, we took a moderate effect size ($\eta^2 = 0.059$), with a statistical power of 0.8 and a significance level of 0.05. Derived the need for a minimum of 24 subjects.

3 Results

The effects of the six-week intervention on punching ability and strength in the three groups of subjects are shown in Figures 1, 2.

3.1 Within-group comparisons

OL: SPF increased (pre vs. post: 2458.96 ± 118.25 vs. 2703.33 ± 267.84; $p = 0.003$; 95% CI: −397.48 to −91.26); SPP increased (pre vs. post: 20936.76 ± 1247.06 vs. 23415.56 ± 2449.65; $p = 0.001$; 95% CI: −58.28 to −17.99); 10 PS increased (pre vs. post: 46.58 ± 2.15 vs. 50.92 ± 2.71; $p = 0.000$; 95% CI: −5.61 to −3.06); 30 PS increased (pre vs. post: 138.83 ± 2.72 vs. 146.50 ± 2.75; $p = 0.000$; 95% CI: −9.60 to −5.74); 60 PS increased (pre vs. post: 181.00 ± 4.05 vs. 210.25 ± 15.98; $p = 0.000$; 95% CI: −34.94 to −23.57); SQ increased (pre vs. post: 62.92 ± 4.50 vs. 71.25 ± 3.11; $p = 0.000$; 95% CI: −10.91 to −5.76); CMJ increased (pre vs. post: 27.65 ± 0.64 vs. 31.83 ± 1.59; $p = 0.000$; 95% CI: −5.31 to −3.03).

TL: SPS decreased (pre vs. post: 8.42 ± 0.56 vs. 7.97 ± 0.54; $p = 0.026$; 95% CI: 0.06–0.85); SPP decreased (pre vs. post: 20898.01 ± 1774.184 vs. 19582.39 ± 1668.526; $p = 0.049$; 95% CI: 0.094–40.39); 10 PS increased (pre vs. post: 45.92 ± 1.56 vs. 47.5 ± 2.39; $p = 0.016$; 95% CI: −2.86 to −0.31); SQ increased (pre vs. post: 62.50 ± 4.52 vs. 72.92 ± 2.57; $p = 0.000$; 95% CI: −12.99 to −7.85); and CMJ increased (pre vs. post: 24.42 ± 1.52 vs. 29.23 ± 1.91; $p = 0.000$; 95% CI: −5.81 to −3.53).

3.2 Between-group comparisons

The results of one-way repeated-measures analysis of variance showed that the improvement effect of SPP was significantly different across groups ($F = 7.38$; $p = 0.004$; $\eta^2 = 0.402$), and OL was significantly higher than that of TL ($p = 0.012$; 95% CI: 3.992–32.017). The improvement effect of 10 PS was significantly different in groups ($F = 15.394$; $p = 0.000$; $\eta^2 = 0.583$), and OL was significantly higher than CG ($p = 0.000$; 95% CI: 7.066–14.431). The improvement effect of 30 PS was significantly different in groups ($F = 25.941$; $p = 0.000$; $\eta^2 = 0.702$), and OL was significantly higher than TL ($p = 0.000$; 95% CI: 3.552–8.820) and CG ($p = 0.001$; 95% CI: 2.135–7.005). The improvement of 60 PS was significantly different between groups ($F = 35.454$; $p = 0.000$; $\eta^2 = 0.763$), and OL was significantly higher than TL ($p = 0.001$; 95% CI: 6.225–20.043) and CG ($p = 0.000$; 95% CI: 10.015–20.224). There were significant differences in improvement of SQ by group ($F = 20.022$; $p = 0.000$; $\eta^2 = 0.645$), OL ($p = 0.002$; 95% CI: 5.859–22.508) and TL ($p = 0.001$; 95% CI: 8.526–26.694) were significantly higher than CG. The improvement of CMJ was significantly different by group ($F = 18.991$; $p = 0.000$; $\eta^2 = 0.633$), OL ($p = 0.000$; 95% CI: 9.060–19.255) and TL ($p = 0.002$; 95% CI: 8.004–30.587) were significantly higher than CG.

4 Discussion

The objective of this study was to examine the impact of two distinct approaches to strength training, Optimal load training and traditional load training, on the punching ability and strength of boxers. Our findings suggest that optimal load training may better align with the specific demands of boxing and could be more effective in enhancing punching ability compared to traditional load training and routine team training. In contrast, traditional load training tends to focus more on improving strength.

4.1 The effect of optimal load training on punching ability

The OL made the subject's power development more in line with the demands of boxing, enhance the mechanical work performed during punches, and indirectly improve the economy of the subject's punches. "Economy" represents a complex interplay of physiological and biomechanical factors (Barnes and Kilding, 2015), "punching economy" is defined as the energy demand under the assumption that the athlete utilizes as many effective punches as possible in a boxing match. This led to the development of regeneration of the subject's muscular endurance or explosive power. In contrast, the TL resulted in a decline in SPS, SPF, SPP, CPS, CPP, and 30 PS, and there was a significant decrease in SPS and SPP. The rationale behind this phenomenon was investigated in the context of the movement pattern and force generation characteristics of boxing. The primary objective of strength training for boxers is neuromuscular capacity training, rather than muscle hypertrophy training. For boxers, such as those engaged in bench press training, the objective is to link the chest, shoulders, and arms together to form a synergistic force, rather than solely to improve muscular strength. The traditional training load arrangement tends to focus primarily on improving maximum strength reserve, which may result in less emphasis on achieving the optimal ratio of force and speed. This approach can make it challenging to fully maximise punching ability.

The present study suggests that the ability of OL to enhance the subjects' punching speed may be attributed to the effectiveness of the targeted training loads in this loading arrangement in improving the subjects' neuromuscular coordination and facilitating greater fast muscle fibre recruitment (Pareja-Blanco et al., 2017a; Sañudo et al., 2020). The kinetic chain in boxing necessitates a force transfer from the lower limb to the arm and then from the core to the arm to complete the force release, due to the existence of this chain. Consequently, the quantity of power generated during the lower extremity stomp will have a direct impact on the rate of growth, and thus on the speed of the punch when the upper extremity performs the terminal release. The optimal load that produces the maximum power output can increase the force of the lower limb stirrups by improving the neural control of the muscles (Enoka, 2012; Heckman and Enoka, 2012), which is conducive to the increase of the punching speed. Furthermore, the speed of power transmission in the kinetic chain is also influenced by the excitation and inhibition of the motor nerve centre in the cerebral cortex and the coordination between the upper and lower limbs. Existing studies have demonstrated that training at the optimal load that can produce the maximum power output optimises the effect of these factors (González-Badillo et al., 2011).

Concurrently, OL augmented the subjects' punching force, which may be attributed to the optimised ratio of load intensity and load volume in this loading arrangement, thereby aligning the training more closely with the demands of boxing. Furthermore, the training aimed at maximising the power output may effectively enhance the sensitivity of calcium ions in the myocytes, potentially leading to an enhancement of the muscle's ability to contract rapidly. Concurrently, the muscle contraction force is augmented by modifying the pennation angle (Blazevich et al., 1985). The rationale behind training with optimal load is that it benefits the organism by recruiting more fast muscle fibres. This is because an appropriate load effectively prevents fatigue from occurring prematurely, and during training, subjects can maintain high neural excitability, which accelerates the conduction rate of action potentials in the nerves. This, in turn, provides the organism with the possibility of recruiting more fast motor units (Pareja-Blanco et al., 2017b), which is ultimately manifested in the enhancement of the subject's punching force. Previous studies have also corroborated this hypothesis. A study on the efficacy of velocity loss based strength training, conducted by Galiano et al., demonstrated that the modulation of the amount of load based on the subject's real-time state during strength training was an effective method for improving the subject's maximal strength and lower extremity explosive power (Galiano et al., 2022). Folland and Sant Anielo et al. demonstrated in their study that suitable resistance training was beneficial for promoting changes in the pennation angle of muscle fibres to increase muscle contraction force (Folland and Williams, 2007; Santanielo et al., 2020).

As there is a significant correlation between punching power and punching force and speed, a change in either force or speed will cause a change in power (McGill et al., 2010; Loturco et al., 2014). In this study the SPF of the OL showed a significant increase and the results of the SPP were in line with this, also showing a significant increase.

The number of sandbag punches in 10, 30 s and 1 min can be used to assess the subject's muscular endurance. Boxers must compete in multiple rounds, and the short and multiple power generation pattern and short intervals between rounds require that the boxers not only have the force and speed to perform well in the initial rounds of the competition, but also have the muscular endurance to cope with later rounds. Conversely, a reduction in punching speed and force will ultimately affect the performance of the match. However, according to related research, the ATP-CP system (Adenosine Triphosphate-Creatine Phosphate System) and CP reserve in human skeletal muscle can only meet approximately 50 intense muscle contractions. The ATP-CP system provides immediate energy for short bursts of high-intensity activity (up to 10 s) by using stored ATP and creatine phosphate in muscles, and the glycolysis is the breakdown of glucose into pyruvate in the cytoplasm, producing a net gain of 2 ATP. Under anaerobic conditions, pyruvate is converted into lactic acid, leading to muscle fatigue (Gottlieb et al., 2021). The number of punches a boxer throws in a match is much higher than 50, which requires a boxer to have a good anaerobic energy supply capacity and reserves of energy substances such as ATP and CP. In addition to the aforementioned attacking and defending movements, boxers must also perform a multitude of variable pace adjustment movements, which are dependent on the aerobic oxidative energy supply. Concurrently, boxers must be able to make rapid attacks at the appropriate time, which necessitates the ability to perform a large number of explosive force movements in short intervals. This inevitably results in the production of a considerable amount of lactic acid. The aerobic capacity is directly related to the efficiency of lactic acid removal, which directly affects the athlete's physical status at the late stage of the match. Therefore, it is possible that the movement pattern and force generation characteristics of OL are more in line with the needs of boxing. This speculation suggests that the strength gains achieved through the training intervention may transfer effectively to actual boxing performance, potentially improving the economy of punching and indirectly optimizing the distribution of physical energy during the punching process. The present study demonstrated that the 60 PS of OL was improved by 16.08% ± 7.09%, which was the most significant indicator of improvement following the training intervention. This finding corroborates the aforementioned arguments.

4.2 The effect of optimal load training on strength

In terms of strength, the BP, SQ and CMJ tests reflected the subjects' upper limb maximal strength, lower limb maximal strength and lower limb explosive power, respectively. Following the six-week training intervention, the strength indicators of OL and TL showed different degrees of improvement. Nevertheless, the improvement effect of TL was significantly superior to that of OL, and the pre- and post-test comparisons of the results of the SQ and CMJ demonstrated highly significant differences. In contrast, no significant difference was observed in the results of the BP of the OL.

This result demonstrates the distinction between the two contrasting approaches to load arrangement for strength training, in terms of the training effect and the adaptive changes produced on the organism. Strength training, as a fundamental component of the training regimen for boxers, must be aligned with the objectives of the boxing programme. On the one hand, it should facilitate the development of strength in all regions of the athlete's body. On the other hand, it should also consider the need to enhance the athlete's punching ability while maintaining the quality of their technical movements. It is essential to ensure that the load arrangement during training meets the needs of actual combat, not only to improve the strength reserve, but also to consider whether the strength acquired through training can improve punching ability without affecting the quality of the technical movements of the boxer. The findings of this study indicate that TL is primarily concerned with enhancing the subjects' fundamental strength. During training, the strength of a specific muscle group in the subjects is augmented, yet the study fails to address the question of how to transform the subjects' accumulation of basic strength into the output capacity required during competition. In boxing, both force and speed are considered to be winning factors. However, the application of pure strength training may result in an increase in the athlete's body weight, impairment of muscle elasticity and a reduction in the rapid contraction of muscles, which in turn may lead to a decrease in the boxer's punching speed (Behm et al., 2017). The optimal ratio of load intensity and volume in training is essential for effective punching. This is in line with the core idea of the optimal load training theory, which states that training under the optimal load is necessary to obtain the maximum power output.

Consequently, the training objectives of OL and TL diverge. TL may be more pertinent to the strength accumulation phase of a boxer's sporting career, which can optimise their strength reserves and circumvent deficits. For elite boxers who have already established their own fighting style, OL will be more targeted and efficacious for them. In the context of the current boxing world, which is focused on intense confrontation, it is important to consider how to maximise the simultaneous increase in force and speed, improve the quality and quantity of effective punches, and delay fatigue. This is in order to ensure that the athletes are able to maintain their performance in the high-lactic acid state of sustained athleticism.

5 Limitation

In this study, the subjects were all female and further research is needed to determine whether the conclusions drawn are equally applicable to male boxers; due to conditions, this study was not able to modulate the female physiological cycle within the 6-week intervention, and athletes' athletic performance may be influenced by hormone levels; this study only investigated the effects of OL and TL on boxers' punching ability from an athletic performance perspective and did not include a mechanism-based study, which can be further demonstrated from a physiological mechanism perspective in future studies.

6 Conclusion

This one study suggests that TL may enhance the development of muscular strength, while OL appears more effective in improving punching ability, potentially facilitated by the individualized and targeted loading scheme. In terms of practical application, OL may be more applicable to elite athletes, as their strength has reached a point of stability at this stage, and they have developed their own athletic style, which requires a training arrangement that is more conducive to their needs. TL may be more applicable to the initial stage of an athlete's career, which is conducive to the accumulation of strength.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Shanghai University of Sport Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

WC: Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. YC: Data curation, Software, Validation, Visualization, Writing–review and editing. DW: Funding acquisition, Resources, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effect of whole-body cryotherapy on recovery after high-intensity training in elite rowers

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The purpose of this study was to investigate the effect of whole-body cryotherapy (WBC) on acute recovery after a single high-intensity training day. Twelve elite professional male rowers from the national aquatic training base. They were randomly divided into a WBC group (n = 6) and a control group (CON group, n = 6). They performed a high-intensity training program, with a single session immediately followed by WBC (–110°C, 3 min) or recovered naturally for 3 min (CON group). Rowing performance, skin temperature, heart rate, blood pressure, and blood lactate concentrations were recorded before training, immediately, 5 min, and 15 min after the intervention. Blood samples were collected early in the morning of the day of intervention and that of the following day. The results indicated that 1) the blood lactate concentrations after WBC were significantly lower than pre-training ($p < 0.05$); 2) the maximum power significantly decreased immediately after WBC compared to pre-training ($p < 0.05$); 3) a significant main effect of time was observed for average speed, which significantly decreased after WBC ($p < 0.05$); 4) a significant main effect of time for blood parameters was observed. Specifically, hematocrit, cortisol, and hemoglobin were significantly lower after WBC than pre-intervention, whereas testosterone/cortisol was significantly higher than pre-intervention ($p < 0.05$). The results of this study showed that a single session of WBC had a positive effect on accelerating the elimination of blood lactate after HIT, but did not significantly change rowing performance and physiological parameters. A single session of WBC was not an effective strategy for elite rowers for acute recovery after HIT.

KEYWORDS

whole-body cryotherapy, rowers, functional recovery, high-intensity training, blood lactate

1 Introduction

Rowers follow rigorous, carefully planned training programs designed to perform at their best in important competitions. High-intensity training (HIT) is inherent to the training programs of rowers and aims to apply a sufficiently high training pressure to further stimulate the body to improve athletic performance. Consequently, HIT may create an imbalance between training load and recovery of bodily functions, This can lead athletes into a state of overtraining, which ultimately leads to a decline in performance, immunity, and athleticism. Previous studies have demonstrated that HIT training for elite handball players increases hormonal and systemic inflammation throughout the body (Zwetsloot et al., 2014; Meckel et al., 2009). It has also been noted that failure to recover promptly after

HIT may lead to symptoms such as increased fatigue, adverse mood changes, and a sustained decline in athletic performance (Le Meur et al., 2013; Le Meur et al., 2014). However, if there is an appropriate recovery period, an "overshoot" effect occurs, whereby physiological responses compensate for the training-related load and the athlete can perform better (Schaal et al., 2015). Therefore, methods that accelerate physical recovery after HIT may play an important role in improving performance.

Currently, different body cooling methods such as massages, active recovery, complete rest, and medications, have been demonstrated to restore the body's functional state. Massages can help reduce muscle soreness and improve blood circulation, typically requiring several hours to a day to see benefits (Best et al., 2008). Active recovery, which involves low-intensity exercises, can promote blood flow and muscle repair, with optimal effects often observed within 24–48 h (Dupuy et al., 2018; Huyghe et al., 2018). Full rest allows the body to recover naturally over a period of days, depending on the extent of fatigue and muscle damage (Kellmann et al., 2018; Grandou et al., 2020). Medications, such as anti-inflammatories, can provide quicker relief from pain and inflammation but should be used judiciously due to potential side effects (Schellack and Ncube, 2021).

Whole-body cryotherapy (WBC) presents several advantages over these traditional methods, in which the participant is continuously exposed for 3 min to a very low temperature and dry freezer or cryo chamber (whose temperature ranges between −110°C and −160°C) (Rose et al., 2017). It works by applying a short, high-intensity cold stimulus to the skin surface all over the body, thereby relieving pain, treating inflammation, as well as improving athletic performance, and facilitating the rehabilitation process (Rose et al., 2017; Bouzigon et al., 2016; Mourot, Cluzeau, and Regnard, 2007; Christmas et al., 2016). Lactate is a widely recognized biomarker for assessing exercise intensity and the efficacy of recovery strategies. Various recovery techniques, such as passive rest, active recovery, and cold water immersion, have been shown to facilitate lactate clearance to varying degrees (Menzies et al., 2010; Hohenauer et al., 2015; Dupuy et al., 2018). However, WBC stands out for its pronounced effect on reducing blood lactate levels, making it a particularly effective method for enhancing recovery following high-intensity exercise (Wiewelhove et al., 2019). Unlike other methods, WBC's extreme cold exposure may accelerate the reduction of lactate levels more effectively, thus mitigating muscle fatigue and shortening recovery time. This enhanced lactate clearance is crucial for maintaining and improving athletic performance (Thomas et al., 2007). Furthermore, WBC can influence hormonal responses, including reductions in cortisol and improvements in testosterone levels, which are vital for recovery and muscle repair (Hausswirth et al., 2011a). A recent review found that WBC was able to have significant effects on the physiological and biochemical parameters of athletes (Banfi et al., 2010). These results included a reduction in the release of pro-inflammatory cytokines, modulation of antioxidant status to adapt to environmental changes, and a reduction in the positive effects on muscle enzymes associated with muscle damage, such as creatine kinase and lactate dehydrogenase. This intervention approach has shown a wide range of positive effects across different athletic disciplines, not limited to improvements in physiological and biochemical parameters. (Ziemann et al., 2012a) documented that elite tennis players who underwent WBC at −120°C twice a day for a total of 5 days had higher stroke accuracy compared to an untreated control group; Krueger observed that WBC significantly improved acute recovery of long-distance runners during HIT at appropriate temperatures (2015). Although WBC has shown positive effects across multiple sports disciplines, research on its effectiveness and applicability in the specific field of rowing may still be insufficient. Rowing is a high-intensity, endurance-demanding sport, and its physical demands and recovery processes may differ from those of other types of sports.

WBC presents several advantages over these traditional methods. WBC involves exposing the entire body to extremely low temperatures for a short period, which can provide uniform and deep cooling. It has been shown to reduce pro-inflammatory cytokines, modulate antioxidant status, and decrease muscle damage markers such as creatine kinase and lactate dehydrogenase (Rose et al., 2017). Importantly, WBC has been associated with significant reductions in blood lactate levels, which is crucial for enhancing recovery after high-intensity training (Wiewelhove et al., 2019). Elevated lactate levels post-exercise can contribute to muscle fatigue and delayed recovery; hence, effective lactate clearance is beneficial for athletic performance (Duffield et al., 2010). Furthermore, WBC can influence hormonal responses, including reductions in cortisol and improvements in testosterone levels, which are vital for recovery and muscle repair (Hausswirth et al., 2020).

Therefore, the purpose of this study was to investigate the effects of a single session of WBC (3 min at −110°C) on recovery from HIT in elite rowers. It was hypothesized that a single session of WBC after HIT would induce modifications of biochemical and hematological parameters, which could be beneficial for accelerating recovery in elite rowers.

2 Materials and methods

2.1 Participants

G*power software (3.0.1, Univ. Kiel, Kiel, Germany) was used for priori estimation of the sample size (*a priori* power analysis) based on the prior data (salivary testosterone concentrations changes in the WBC group and the control group pre-exercise and immediately, 2 h and 24 h post-exercise, $f = 0.70$) showed that the minimum sample size required when performing repeated measures two-way ANOVA was 6 ($\alpha = 0.05$, $\beta = 0.2$) (Russell et al., 2017a). Therefore, twelve elite male rowers (age 19.1 ± 8.4 years, height 193.7 ± 4.8 cm, weight 87.8 ± 8.4 kg, years of training 5.7 ± 3.1 years, and the best race time for 2 km 6:33 ± 0: 47 min) with a sports grade of national level or higher were recruited from the national aquatic training base with no history of cold therapy intervention. The participants were randomized into a WBC group (n = 6) and a control group (CON, n = 6). They were asked to avoid alcohol and caffeine for 24 h before the tests and to adhere to their usual diet throughout the testing period. They were prohibited from using any other recovery methods, including physical therapy, nonsteroidal anti-inflammatory drugs, etc. Before the experiment, the participants were informed about the purpose and procedures of the study and written informed consent was obtained from the team coaches and the Aquatic Programmes Centre. The participants all

TABLE 1 High-intensity training program.

Time	Training protocol	Training intensity
8.00 9.30	Water training 26 km	Moderate
9.45 11.45	25 min of speed skating*4	High
14.00 15.10	Strength training	High
15.30 15.50	Running 12 laps (approximately 5 km)	Moderate

signed an informed consent form and the study was ethically certified by the Ethics Committee of Ningbo University (No. TY2023026).

2.2 Procedure

Each participant was asked to perform a 10 s maximal strength continuous rowing (Concept II RowErg, Concept II company, United States). This test was conducted both before (in a rested state) and immediately after a 1-day high-intensity training session (Table 1), as well as at the 5th and 15th minutes post-training (Lucertini et al., 2017). During the experiment, the participants were asked to complete 5 consecutive rows at maximal power to the best of their ability. Body temperatures (forehead, thighs, arms, and thighs), maximal power, energy expenditure, average speed, and segmentation time were recorded. The rowing team doctor cooperated in collecting venous blood samples (6 mL: 2 mL from the purple tube, and 4 mL from the red tube) from the elbows of the participants in the fasting state at 6:00 a.m. on the day of the high-intensity training and at the same time on the following day. To avoid the paddling test performed by the participants affecting the accuracy of the blood lactate collection, the blood lactate concentrations were therefore collected at the same time 1 week apart, specifically pre-HIT and immediately after the training session, at the 5th minute, and the 15th minute (Figure 1).

2.3 Intervention

After a day of HIT, the WBC group was subjected to cryotherapy intervention using a freezing chamber (Cryo°Cabin, Cryotech Nordic company, France). The chamber was pre-set to −110°C and continuously cooled for 300 s. Following the pre-cooling phase, the temperature was maintained at −110°C to keep it low temperatures. At the end of the training session, the participants in the WBC group were required to dry their bodies, remove all metal objects, and wear disposable cotton shoes and gloves. Subsequently, participants entered the cryotherapy chamber for 3 min of ultra-low temperature recovery at −110°C (Missmann et al., 2016). The height of the chamber was adjusted so that the shoulders aligned with its upper edge, leaving the area above the shoulders outside the chamber to prevent nitrogen gas inhalation. Throughout the intervention, participants' heads were kept outside the chamber to avoid nitrogen inhalation, with a medically qualified doctor present to ensure safety and respond to emergencies. Additionally, the trial performer assessed participants' wellbeing every minute and monitored changes in skin color and facial expression. A first aid kit was readily available in the experimental treatment room to address any potential hazards. The CON group was asked to recover naturally for 3 min.

The WBC intervention was repeated at the same time after a 1-week interval. The intervention protocol remained consistent with

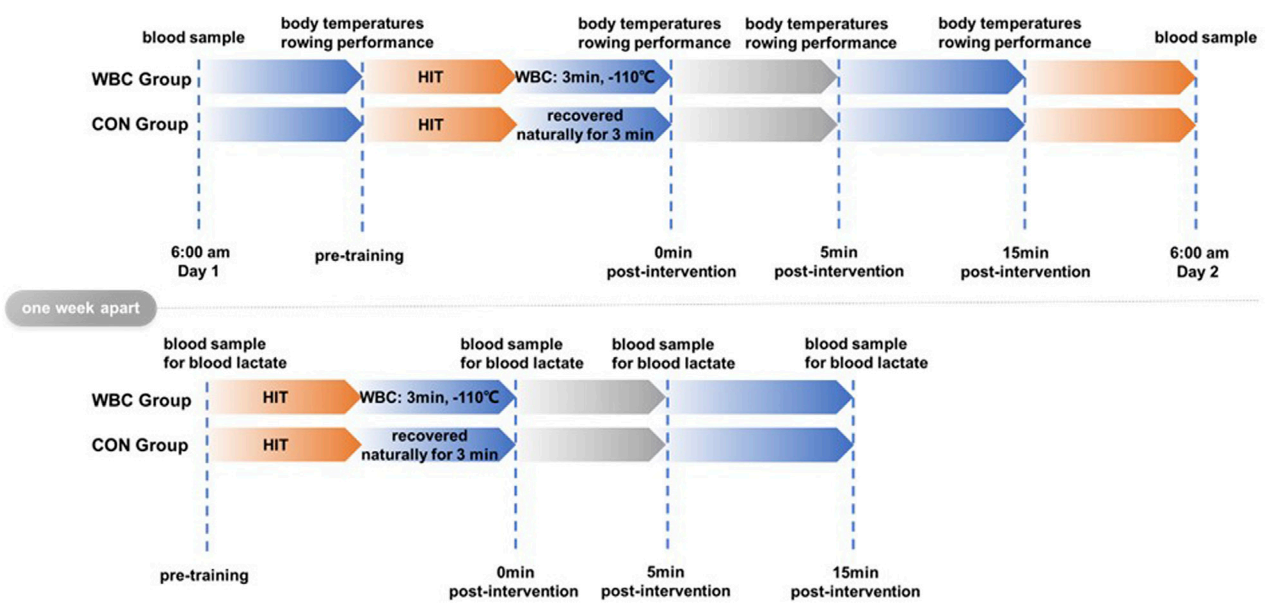

FIGURE 1
Experimental flow chart.

the procedures implemented during the initial week. Blood samples were collected in both groups from the earlobes for blood lactate testing in a resting state before the training, immediately, 5, and 15 min after the intervention, respectively.

2.4 Data processing

The slip distance (m), segment time (s), energy consumption (cal), maximum power (W), and average speed (m/s) were calculated using the concept II dynamometer (RowErg, Concept II, United States)). Beckman SYNCHRON CX®5 Pro automatic biochemical analyzer (Beckman, United States) was used to determine creatine kinase (CK). Beckman ACCESS®2 automatic chemiluminescent immunoassay analyzer (Beckman, United States) was used to determine white blood cell, red blood cell (RBC), hematocrit (HCT), cortisol (C), testosterone (T), cortisol/testosterone (T/C), hemoglobin (HGB). EKF glucose lactate analyzer (Biosen C-Line, Germany) was used to analyze blood lactate concentration in the participants' earlobe blood. An electronic sphygmomanometer (HEM-7122, Omron, Japan) and thermometer (MC-720, Omron, Japan) were used to measure heart rate, diastolic blood pressure, systolic blood pressure, forehead temperature, arm temperature, and thigh temperature.

2.5 Statistical analysis

The data are presented as mean ± standard deviation (x ± s). All data were analyzed using SPSS statistical software (IBM SPSS v22.0, IBM Corp.). Shapiro-Wilk test was conducted to assess whether the data followed a normal distribution. A 2 × 4 repeated measure analysis of variance (ANOVA) was utilized to analyze the effects of different time points (pre-training, immediate post-intervention, 5 and 15 min post-intervention) on exercise recovery outcomes (rowing performance, skin temperature, blood pressure, and blood lactate concentration) within and between the two groups (WBC group versus CON group). A 2 × 2 repeated measure ANOVA was employed to analyze the biochemical indicators on both the morning of the training day and the morning after training. If ANOVA revealed a significant interaction or main effect, the Bonferroni test was used. Paired eta squared (η^2) was used as a measure of ANOVA effect size with 0.01, 0.06 and 0.14 considered small, medium and large, respectively. Cohen's d was used as a measure of *post hoc* comparisons effect sizes with 0.2, 0.5 and 0.8 considered small, medium and large, respectively. Statistical significance was accepted at $\alpha = 0.05$.

3 Results

3.1 Rowing performance

The results showed that there was a significant interaction between group and time on the maximum power during 10s maximal strength continuous rowing ($p < 0.05$, $\eta^2 = 0.262$, Table 2). Post hoc analyses revealed that the maximum power in the WBC group significantly decreased immediately after the intervention compared to pre-training ($p < 0.05$, Cohen's $d = 0.475$, Figure 2). A significant main effect of time was observed for average speed ($p < 0.05$), which significantly decreased immediately (Cohen's $d = 1.441$), 5 (Cohen's $d = 1.169$) and 15 min post-intervention (Cohen's $d = 1.134$) compared to pre-intervention, and significantly decreased at 15 min post-intervention compared to at 5 min post-intervention (Cohen's $d = 0.909$). No significant differences were found for the segmentation time, energy consumption, and glide distance ($p > 0.05$).

3.2 Skin temperature, heart rate, and blood pressure

The results demonstrated a significant interaction between group and time on the temperatures of the forehead ($p < 0.05$, $\eta^2 = 0.413$, Table 3), upper arm ($p < 0.05$, $\eta^2 = 0.832$, Table 3), and thigh ($p < 0.05$, $\eta^2 = 0.879$, Table 3). Post hoc analyses revealed that the temperatures in the WBC group were significantly lower than those during the pre-training immediately after the intervention (Cohen's $d_{forehead} = 0.943$, Cohen's $d_{upper\ arm} = 0.892$, Cohen's $d_{thigh} = 1.256$) and at the 5 min post-intervention (Cohen's $d_{forehead} = 0.937$, Cohen's $d_{upper\ arm} = 1.093$, Cohen's $d_{thigh} = 0.846$), and were also significantly lower compared to the CON group ($p < 0.05$, Cohen's $d_{forehead} = 1.198$, Cohen's $d_{upper\ arm} = 0.931$, Cohen's $d_{thigh} = 1.249$, Figure 3). However, heart rate and blood pressure indicators were not significantly different before and after the intervention ($p > 0.05$).

3.3 Blood parameters

The results of the study showed a significant interaction effect of group and time on blood lactate concentration ($p < 0.05$, Table 4). Post hoc analysis revealed that blood lactate concentrations in the WBC group immediately (Cohen's $d = 1.158$) and 5 min (Cohen's $d = 1.365$) after WBC were significantly lower than pre-training and significantly lower than the CON group (Cohen's $d = 0.877$, Figure 4); the blood lactate concentration in the WBC group at 15 min after WBC was significantly higher than pre-training (Cohen's $d = 1.214$), but did not differ significantly from the CON group ($p > 0.05$).

The results showed that there was no interaction for all biochemical indices ($p > 0.05$), but the significant main effect of time was observed ($p < 0.05$, Table 5). Specifically, HCT ($\eta^2 = 0.325$), C ($\eta^2 = 0.673$), and HGB ($\eta^2 = 0.396$) were significantly lower after the intervention than pre-intervention ($p < 0.05$) whereas T/C was significantly higher than pre-intervention ($\eta^2 = 0.551$, Figure 5).

4 Discussion

The current study aimed to investigate the effects of WBC (3 min at −110°C) on acute recovery after HIT in elite rowers. None of the athletes reported any injuries or negative side effects related to the cold exposure, which indicated a single session of WBC applied in the current study, may be administered without health risk in elite athletes. The main finding of this study was that

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TABLE 2 Effect of a single session of whole-body cryotherapy (WBC) on 10s maximal strength continuous rowing performance (x±SD).

Variables	Groups	Pre-training	Immediately after WBC	5 min after WBC	15 min after WBC	*p*-value		
						Interaction (η^2)	Group (η^2)	Time (η^2)
MP (W)	WBC	828.5 ± 142.5	688.1 ± 116.1*	685.0 ± 80.7	701.6 ± 55.5	0.026 (0.262)	0.825 (0.005)	0.008 (0.322)
	CON	722.8 ± 84.1	732.5 ± 100.5	697.8 ± 117.5	705.3 ± 75.1			
ST (s)	WBC	93.6 ± 5.0	96.1 ± 4.2	96.1 ± 4.9	96.8 ± 3.4	0.696 (0.156)	0.788 (0.008)	0.599 (0.198)
	CON	94.8 ± 4.1	95.6 ± 3.9	95.0 ± 4.8	98.8 ± 3.3			
EC (cal)	WBC	8.1 ± 1.1	7.5 ± 1.0	7.3 ± 1.1	7.3 ± 0.8	0.082 (0.548)	0.693 (0.016)	0.312 (0.344)
	CON	7.3 ± 1.0	7.1 ± 0.4	7.8 ± 1.1	7.3 ± 0.5			
GD (m)	WBC	90.0 ± 4.6	88.0 ± 3.3	88.0 ± 7.0	85.0 ± 2.6	0.173 (0.445)	0.970 (0.001)	0.822 (0.102)
	CON	86.8 ± 3.3	87.4 ± 3.0	87.1 ± 4.6	88.8 ± 6.4			
AS (m/s)	WBC	54.5 ± 5.8	$47.2 \pm 4.2^{\#}$	$48.0 \pm 5.3^{\#}$	$44.0 \pm 3.0^{\#\dagger}$	0.406 (0.291)	0.793 (0.007)	0.030 (0.653)
	CON	51.3 ± 6.0	$46.6 \pm 4.8^{\#}$	$47.8 \pm 4.1^{\#}$	$45.1 \pm 3.0^{\#\dagger}$			

CON, control group; MP, maximum power; ST, segmentation time; EC, energy consumption; GD, glide distance; AS, average speed; *significant interaction between group and time, the difference compared to the pre-training, $p < 0.05$; $^{\#}$significant main effect of time, the difference compared to the pre-training, $p < 0.05$; †significant main effect of time, the difference compared to 15 min after WBC, $p < 0.05$.

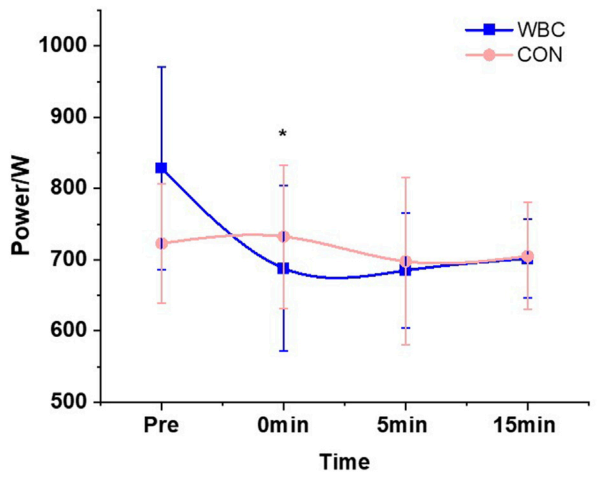

FIGURE 2
Effect of a single session of whole-body cryotherapy (WBC) on the maximum power during 10 s maximal strength continuous rowing performance (x ± SD). CON, control group. *significant difference compared to the pre-training within the WBC group, $p < 0.05$.

the blood lactate concentrations and the maximum power decreased significantly in the WBC group after a single session of WBC. However, there were no significant effects on other blood parameters and exercise performance.

The results of this study highlighted the impact of WBC on blood lactate concentration recovery post-exercise. Specifically, the blood lactate concentrations in the WBC group immediately and 5 min after WBC were 87.1% and 82.5% of those in the CON group at the same moment, respectively. These results indicated that the recovery of blood lactate in the WBC group was significantly faster than that in the CON group, which proved the facilitating role of WBC on the rapid recovery of blood lactate levels in rowers after high-intensity training. This result was similar to that of Wilson and Shepler. (2017) who explored the difference in blood lactate levels between the sedentary and WBC (−120°C, 3°min) groups among Brazilian jiu-jitsu athletes after strenuous exercise. Their study revealed that the WBC group had significantly lower blood lactate concentrations than the sedentary group at both the 10th and 15th minutes post-exercise. Similarly, (Lee and Jeong, 2003) assessed the differences in the rate of blood lactate recovery among seven athletes following a 400 m run through the ice and passive recovery methods. The findings indicated that the blood lactate concentration during the recovery phase was significantly lower in the ice recovery group than that of the passive recovery group in the 5th minute of the recovery period. It has been demonstrated that as a metabolic product of glycolysis for energy during exercise, lactate is produced in large amounts after intense exercise (Hoff et al., 2016). After WBC, the temperature of each part of the participants decreased rapidly, and this study showed that the temperature of the forehead, thighs, and arms decreased by an average of 8.95°C, 13°C, and 11.15°C, respectively, immediately after WBC. Vasodilatation induced by the cold stimulus may be the main reason for the faster rate of blood lactate decrease, and studies have demonstrated that the blood flow is four times higher than normal after WBC and that this rapid blood circulation change can last for hours after exercise and blood lactate metabolism is also more rapid (Bouzigon et al., 2021). Another possibility was that WBC could accelerate functional recovery by reducing muscle catabolic activity thereby reducing blood lactate production (Patel et al., 2019). It is therefore recommended for athletes to integrate WBC into their post-intensive training regimen to enhance recovery processes.

Although this study observed an accelerated clearance of blood lactate after WBC, this effect did not translate into alterations in segmentation time, skating distance, or energy expenditure. The results revealed no significant differences between groups in these parameters, except for a significant reduction in immediate

TABLE 3 Effect of a single session of whole-body cryotherapy (WBC) on the skin temperature, heart rate, and blood pressure (x ± SD).

Variables	Groups	Pre-training	Immediately after WBC	5 min after WBC	15 min after WBC	*p*-value		
						Interaction (η^2)	Group (η^2)	Time (η^2)
PR (times/min)	WBC	72.0 ± 12.9	78.3 ± 14.9	75.3 ± 18.6	75.3 ± 18.6	0.103 (0.519)	0.836 (0.004)	0.166 (0.452)
	CON	76.5 ± 9.1	70.3 ± 5.5	73.8 ± 9.9	69.7 ± 11.8			
SBP (mmHg)	WBC	125.1 ± 6.1	130.0 ± 6.8	131.3 ± 11.0	124.5 ± 6.4	0.433 (0.272)	0.208 (0.153)	0.563 (0.215)
	CON	134.1 ± 5.8	127.5 ± 8.5	129.6 ± 6.5	129.5 ± 5.2			
DBP (mmHg)	WBC	56.1 ± 5.5	61.3 ± 6.9	72.5 ± 13.5	60.8 ± 6.2	0.053 (0.597)	0.339 (0.091)	0.703 (0.153)
	CON	72.0 ± 21.6	59.3 ± 5.8	52.5 ± 5.2	57.1 ± 6.5			
Forehead temperature (°C)	WBC	36.3 ± 0.3	27.3 ± 0.3$^{*\&}$	30.0 ± 0.2$^{*\&}$	36.2 ± 0.3	0.036 (0.413)	0.021 (0.445)	0.015 (0.549)
	CON	36.6 ± 0.2	36.4 ± 0.3	36.4 ± 0.2	36.5 ± 0.2			
Upper arm temperature (°C)	WBC	36.7 ± 0.7	23.7 ± 0.7$^{*\&}$	27.7 ± 2.1$^{*\&}$	35.2 ± 1.6	<0.01 (0.832)	<0.01 (0.886)	<0.01 (0.914)
	CON	36.3 ± 0.2	36.2 ± 0.3	36.3 ± 0.3	36.3 ± 0.2			
Thigh temperature (°C)	WBC	35.9 ± 0.1	24.8 ± 0.4$^{*\&}$	25.2 ± 0.4$^{*\&}$	35.0 ± 3.0	<0.01 (0.879)	<0.01 (0.913)	<0.01 (0.878)
	CON	35.9 ± 0.1	35.9 ± 0.1	35.9 ± 0.0	35.9 ± 0.1			

CON, control group. *significant difference within the WBC group, compared to the pre-training group, $p < 0.05$; $^{\&}$significant difference between the two groups at the same test time, $p < 0.05$; PR, pulse rate; SBP, systolic blood pressure; DBP, diastolic blood pressure.

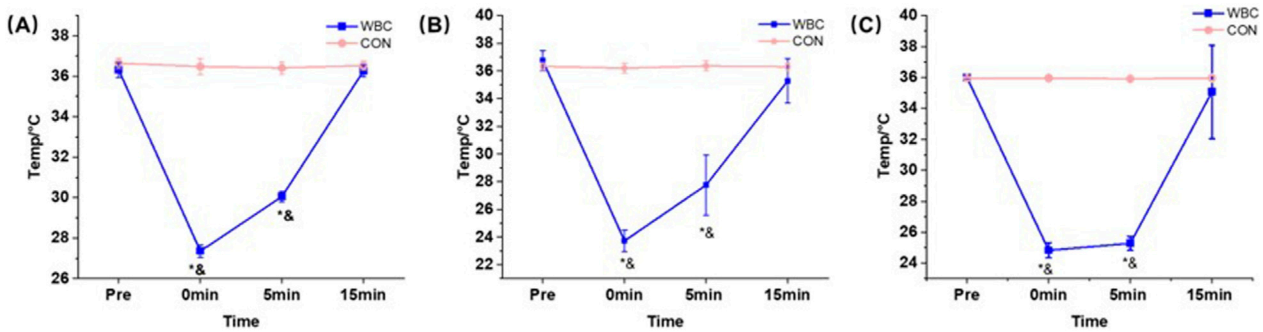

FIGURE 3
Effect of a single session of whole-body cryotherapy (WBC) on the forehead **(A)**, upper arm **(B)**, and thigh **(C)** temperatures (x ± SD); CON, control group. *significant difference within the WBC group compared to the pre-training group, $p < 0.05$; $^{\&}$significant difference between the two groups at the same test time, $p < 0.05$.

TABLE 4 Effect of a single session of whole-body cryotherapy (WBC) on blood lactate concentration (x±SD).

Groups	Pre-training (mmol/L)	Immediately after WBC (mmol/L)	5 min after WBC (mmol/L)	15 min after WBC (mmol/L)	*p*-value		
					Interaction (η^2)	Group (η^2)	Time (η^2)
WBC	0.9 ± 0.1	12.8 ± 1.2$^{*\&}$	10.2 ± 1.3$^{*\&}$	1.9 ± 0.2*	0.013 (0.745)	0.025 (0.532)	<0.01 (0.857)
CON	0.9 ± 0.1	14.7 ± 1.3*	12.4 ± 1.6*	1.9 ± 0.3*			

CON, control group. *significant difference compared to pre-training, $p < 0.05$; $^{\&}$significant difference between the two groups at the same test time, $p < 0.05$.

post-cold therapy maximal power in the WBC group, compared to pre-training levels. Similar to the results of the present study, Russell et al. (2017b) indicated a single session of WBC (−135°, 3 min) had no enhancement effect on immediate short-distance sprinting (15*30 m) in football players, except for elevating testosterone concentrations over 24 h. In addition, Ferreira et al. (2014) found

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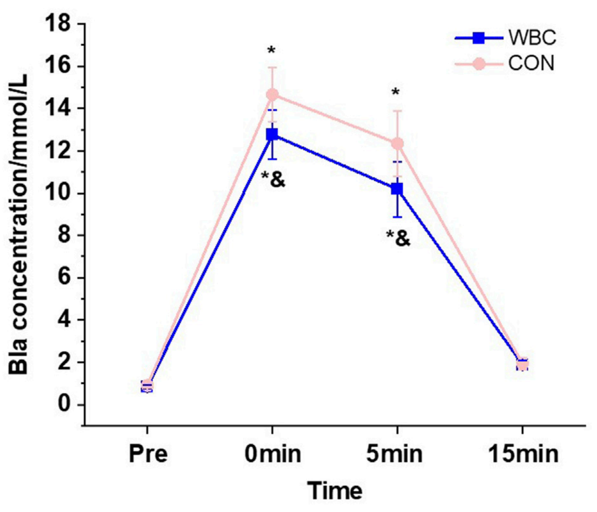

FIGURE 4
Effect of a single session of whole-body cryotherapy (WBC) on blood lactate concentration; CON, control group. *Significant difference compared to pre-training, $p < 0.05$; &significant difference between the two groups at the same test time, $p < 0.05$.

peak maximal elbow flexion moments were reduced 10 min after a single session of WBC (−110°, 3 min) on strong, healthy young men compared to the pre-test. Furthermore, Fullam et al. (2015) found that a single 15-min cryotherapy session on the ankle joints had a negative postural balance. These studies, aligning with the present research, suggested that while WBC might offer certain benefits, such as elevated testosterone levels, its impacts on immediate athletic performance and muscular function can vary, sometimes resulting in no improvement or even negative outcomes. Conversely, other research offered a different perspective on the potential benefits of WBC. Krueger et al. (2015) observed that WBC significantly improved acute recovery during high-intensity exercise at −110°C for 3 min for long-distance runners; (Ziemann et al., 2012b) documented improvements in athletic performance in a group of outstanding tennis players after WBC. They found that athletes who underwent WBC at −120°C twice a day for a total of 5 days had higher stroke accuracy compared to untreated controls. These findings indicated that there were differences in the effectiveness of WBC in enhancing athletic performance and muscle function, highlighting the complexity of the effects of WBC interventions.

There was only a significant main effect of time in the blood parameters, with no significant differences between the groups. Specifically, HCT, C, and HGB were significantly lower after the intervention than pre-intervention, whereas T/C was significantly higher than pre-intervention. This result was consistent with previous studies on a single session of WBC. Jurecka et al. (2023) assessed the effect of a single session of WBC (−130°C, 3°min) on professional runners and showed no significant differences in CK and inflammatory reactants (e.g., white blood cell) after a single

TABLE 5 Effect of a single session of whole-body cryotherapy (WBC) on biochemical indicators (x±SD).

Variables	Groups	Pre	Post	*p*-value		
				Interaction (η^2)	Groups (η^2)	Times (η^2)
RBC (10^3/uL)	WBC	5.1 ± 0.2	5.0 ± 0.1	0.896 (0.002)	0.363 (0.083)	0.170 (0.229)
	CON	5.2 ± 0.2	5.1 ± 0.1			
HCT (%)	WBC	45.5 ± 1.9	44.6 ± 2.1	0.849 (0.004)	0.363 (0.083)	0.048 (0.325)
	CON	46.8 ± 2.9	45.7 ± 1.8			
WBC[1] (10^3/uL)	WBC	5.8 ± 0.7	5.8 ± 0.8	0.370 (0.081)	0.952 (0.001)	0.160 (0.174)
	CON	6.0 ± 0.6	5.7 ± 0.9			
CK (U/L)	WBC	544.8 ± 234.9	404.6 ± 139.3	0.174 (0.176)	0.815 (0.006)	0.477 (0.052)
	CON	509.0 ± 280.2	580.6 ± 405.9			
C (μg/dL)	WBC	27.7 ± 3.5	20.7 ± 2.9	0.839 (0.004)	0.706 (0.015)	0.012 (0.673)
	CON	28.2 ± 4.3	21.8 ± 5.7			
T (ng/dL)	WBC	467.1 ± 121.5	520.0 ± 135.9	0.942 (0.001)	0.151 (0.195)	0.139 (0.206)
	CON	561.0 ± 117.9	619.0 ± 114.5			
T/C	WBC	17.0 ± 4.6	26.2 ± 10.0	0.878 (0.002)	0.359 (0.085)	0.006 (0.551)
	CON	20.2 ± 4.7	30.2 ± 9.7			
HGB (g/dL)	WBC	14.6 ± 0.7	13.4 ± 0.8	0.661 (0.020)	0.350 (0.088)	0.028 (0.396)
	CON	15.1 ± 0.9	14.8 ± 0.7			

WBC[1], white blood cell; RBC, red blood cell; HCT, hematocrit; CK, creatine kinase; C, cortisol; T, testosterone; T/C, testosterone/cortisol; HGB, hemoglobin; WBC, Whole-Body Cryotherapy group; CON, control group.

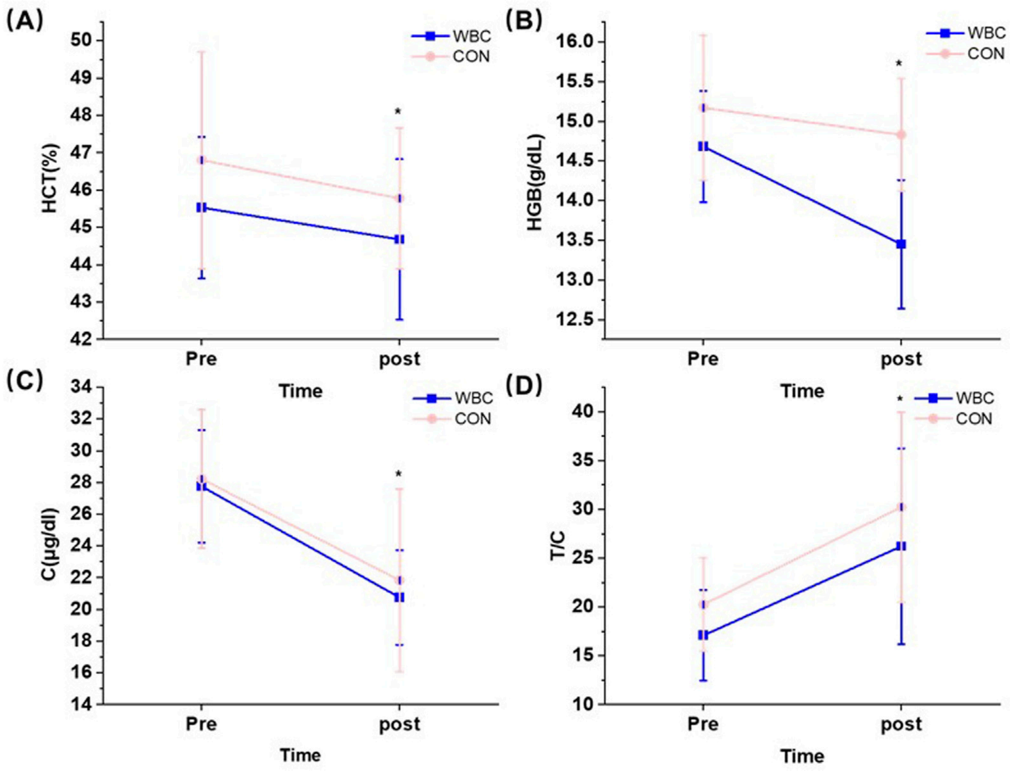

FIGURE 5
Effect of a single session of whole-body cryotherapy (WBC) on HCT **(A)**, HGB **(B)**, C **(C)**, and T/C **(D)** (x ± SD); HCT, hematocrit; HGB, hemoglobin; C, cortisol; T/C testosterone/cortisol; CON, control group; *significant difference compared to pre-training, $p < 0.05$.

session of WBC. A similar result was obtained in the study of Krueger et al. (2015), who found that a single session of WBC did not have a significant effect on leukocytes, C, T, and CK after high-intensity intermittent running exercise. However, it was notable that while acute WBC sessions might not sufficiently impact biochemical indices, repeated exposure could induce significant physiological changes. Banfi et al. (2009) demonstrated that rugby players who underwent a WBC once a day during 5°days of training (−110°C, 3°min) had no effect on their immune parameters but showed a decrease in pro-inflammatory cytokines versus an increase in anti-inflammatory cytokines. Ptaszek et al. (2023). Measured the effect of prolonged WBC (−120°C, 3 min) on blood morphology and rheological parameters in healthy participants and showed that WBC resulted in significant decreases in RBC, HGB, HCT, and positively affected blood rheology. We speculated that this might be due to the cumulative effects of WBC on the recovery mechanisms. A single session of WBC may not produce a strong enough stimulus to elicit marked changes in the biochemical and inflammatory responses. However, repeated sessions of WBC could introduce increased stimulus or load, resulting in enhanced anti-inflammatory responses and blood rheology. This increased stimulus might contribute to enhanced recovery processes, highlighting the importance of considering the duration and frequency of WBC in athletic training regimens. Another potential reason was the exercise intensity before WBC. The participants involved in our study were elite-level rowers, who have adapted to the intensity and cold stress of winter training over a long period. Consequently, reliance on a solitary session of WBC might not be sufficient to cause significant changes in blood indices. This might explain the inconsistency between the present study and that of Pournot et al. (2011) who found significantly lower inflammatory markers in the blood of professional runners after a single session of WBC following simulated cross-country running. This significant observation could be attributed to the unique physiological challenges posed by cross-country running. Specifically, the heavy loads characteristic of this type of running were known to induce substantial muscle structural damage and inflammation, potentially explaining the efficacy of a single session of WBC session in their study (Hausswirth et al., 2011b). Therefore, these findings underscored the importance of considering the intensity of the pre-exercise load as well as the frequency and duration of WBC when evaluating it as a strategy for post-exercise recovery. Lastly, an important aspect that may have affected the results of the trial was the relatively small size of the experimental group. This study should be continued in larger groups.

There are some limitations of this study. Firstly, since we specifically focused on male athletes, female athletes were not included in the study. Females have been indicated to cool down faster than males after WBC (Cuttell et al., 2017), thus it is reasonable to speculate that there are differences in athletic performance, and physiological and biochemical parameters between genders after WBC. Secondly, the participants in this study were all elite athletes who had adopted HIT. The recovery effect of a single session of WBC may be limited for elite athletes.

Therefore, it is recommended that future studies include female athletes and conduct long-term investigations to make the research more comprehensive.

5 Conclusion

The results of this study showed that a single session of WBC had a positive effect on accelerating the elimination of blood lactate after HIT. However, the intervention did not significantly change rowing performance and physiological parameters. A single session of WBC was not an effective strategy for elite rowers for acute recovery after HIT.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the Ethics Committee of Ningbo University (No. TY2023026). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

TH: Conceptualization, Formal Analysis, Investigation, Methodology, Software, Writing–original draft, Writing–review and editing. LD: Conceptualization, Methodology, Writing–review and editing. WW: Methodology, Supervision, Writing–review and editing. JR: Formal Analysis, Methodology, Writing–review and editing. XL: Formal Analysis, Methodology, Writing–review and editing. JL: Conceptualization, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effect of high-intensity interval training and moderate-intensity continuous training on blood lactate clearance after high-intensity test in adult men

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This study compared the effects of High-intensity interval training (HIIT) and moderate-intensity continuous training (MICT) on blood lactate clearance. 21 adult males were equally and randomly assigned to the HIIT and MICT groups, and completed 8 weeks of training. Before the training intervention, after 4 weeks and 8 weeks of training, all subjects were tested for blood lactate levels between 0 and 55 min after the same high-intensity test. The results show that after 8 weeks, blood lactate levels were significantly lower than pre-tests in both the HIIT and MICT groups at “0–55 min” after high-intensity test ($p < 0.05$), and the blood lactate clearance percentage at15-min and 30-min in both groups were significantly higher than the pre-tests ($P < 0.01$). The blood lactate levels in the HIIT group were significantly lower than those in the MICT group at 15 min and 30 min after test ($P < 0.05$), and the blood lactate clearance percentage at 30 min in the HIIT group was significantly higher than those in the MICT group ($P < 0.05$). In conclusion, both HIIT and MICT enhance blood lactate clearance in adult males post high-intensity test, with HIIT demonstrating superior effectiveness, making it a viable alternative to MICT.

KEYWORDS

HIIT, MICT, blood lactate, adult men, train

1 Introduction

Lactic acid is a metabolic product of glycolysis for body energy supply and is rapidly dissociated into lactate and protons (Robergs et al., 2004). The body contains a small amount of lactate at rest, whereas during high-intensity exercise (Astrand et al., 1963) or cardiorespiratory dysfunction (Mungan et al., 2018), the body is in a state of relative hypoxia and lactate concentrations increase dramatically (Brooks, 2018). The metabolic clearance of lactate is essential for improving the acid–base balance and maintaining internal environmental homeostasis and the glycolytic energy supply rate (Juel, 1996). When lactate accumulates in large quantities, it lowers cellular and blood pH and inhibits glycolysis, which in turn affects exercise performance. The generated lactate is mainly removed by the liver, skeletal muscle, cardiac muscle cells, kidney cells, and other tissues and organs through oxidative decomposition, gluconeogenesis, the synthesis of other substances in the liver, sweating, and urination (Brooks et al., 2022).

Studies have noted that athletes have greater lactate clearance capacity than the sedentary general population (Hinojosa et al., 2021), proving that exercise is an effective way to improve the body's lactate clearance capacity. Related studies have shown that the increased aerobic capacity associated with endurance exercise significantly improves the body's lactate clearance capacity (Messonnier et al., 2013; Emhoff and Messonnier, 2023). Moderate-intensity continuous training (MICT) is a traditional method of aerobic capacity training that involves 30–60 min of moderate-intensity aerobic exercise (65%–75% of maximum heart rate) (Locatelli et al., 2024), and has been demonstrated to enhance the aerobic capacity of the body (Weston KS. et al., 2014). High-intensity interval training (HIIT) is a type of interval training involving multiple rounds of high-intensity exercise or sprint interval training (≥80% of maximum heart rate) (Weston M. et al., 2014) interspersed with recovery periods (MacInnis and Gibala, 2017) and has effects similar to those of strength training or endurance training (Hwang et al., 2019). As two distinct training methods for improving aerobic capacity, there is ongoing debate regarding which method is more effective in enhancing aerobic capacity and post-exercise blood lactate clearance. In terms of promoting aerobic capacity, the prevailing view suggests that HIIT is more effective than MICT, as high-intensity exercise elicits a greater physiological response (Gorostiaga et al., 1991; Schjerve et al., 2008; Martins et al., 2016; Su et al., 2019). Conversely, another perspective posits that both methods yield similar effects (Gibala et al., 2006; Cocks et al., 2015). For instance, Cock's (2015) 4-week study found no significant difference in maximal oxygen uptake improvements between HIIT and MICT interventions. Regarding blood lactate clearance, existing research has demonstrated that HIIT can effectively enhance the body's ability to clear blood lactate (Bishop et al., 2008); however, no studies have yet compared the intervention effects of HIIT and MICT directly. Therefore, this study aims to compare the effects of 8 weeks of HIIT and MICT interventions on blood lactate clearance capacity, providing guidance for the public and athletes in achieving optimal load management and recovery strategies in their training. We hypothesized that both HIIT and MICT contribute to the improvement of blood lactate clearance at rest after high-intensity test, but the effect of HIIT may be better.

2 Materials and methods

2.1 Subjects

The subjects of this study were 22 male college students at Beijing Normal University who were not majoring in physical education. These students were randomly assigned by computer to the MICT and HIIT groups, with 11 people in each group. All subjects were in good health, with no acute or chronic diseases; no smoking or drinking habits; no recent history of medication; no serious sports injuries within 1 year; and no previous sports training experience. During the experiment, subjects were asked to maintain a normal routine and not to participate in additional physical activities. One subject dropped out of the experiment because they failed to meet the training requirements, and finally leaving 10 in the HIIT (Age:21.56 ± 1.35 years, Height:177.30 ± 4.42 cm, Weight:71.18 ± 7.01 kg) and 11 in the MICT (Age: 20.95 ± 1.24 years, Height: 178.07 ± 4.76cm, Weight: 72.03 ± 6.31 kg) groups. The study was approved by the Ethics Committee of Beijing Normal University, and the subjects were informed of the purpose and procedure of this experiment and signed an informed consent form before the intervention.

2.2 Interventions

In this study, subjects in the HIIT group performed a 30-s sprint at 85%–95% HRmax, with a 3-min brisk walking or jogging between sets (Weston KS. et al., 2014), before the exercise, the subjects were instructed to run at maximum speed to achieve the specified heart rate. Subjects in the MICT group ran aerobically at an even pace at 65%–75% HRmax (Locatelli et al., 2024), and the maximum heart rate was estimated as "220 - age". To adhere to the principle of progressive overload in exercise training, we required that energy expenditure be approximately 240 kcal during the first 3 weeks (with the HIIT group performing about six to seven sets and the MICT group engaging in about 30 min of exercise), and increase to 300 kcal during the subsequent 5 weeks (with the HIIT group performing about 8-9 sets and the MICT group engaging in about 35–40 min of exercise). This approach was implemented to mitigate the risk of inadequate adaptation to exercise volume or intensity at the onset of the training. Heart rate monitoring was conducted using the Polar H10 (Polar Electro Oy, Kempele, Finland), which has been proven to effectively track heart rate at both rest and during exercise (Schaffarczyk et al., 2022), ensuring that the intended exercise intensity was achieved. Energy expenditure was measured using the wGT3X-BT (ActiGraph, Pensacola, USA), a device commonly employed for assessing physical activity (Mielke et al., 2022); it was secured to the subject's waist during exercise and removed at the conclusion of the session. Both the HIIT and MICT groups participated in the intervention for 8 weeks, 3 times a week, on Mondays, Wednesdays, and Fridays at 7 a.m. In addition, all subjects were asked to maintain a normal diet (prohibition of ketogenic diet, alcohol consumption, *etc.*) during the training period and were asked to keep a daily record to monitor their diet for inspection. Blood lactate clearance was tested in all subjects before the first training (pre-test), after 4 weeks of training (mid-test), and after 8 weeks of training (post-test). High-intensity test was used as a means of inducing blood lactate accumulation. To ensure the repeatability of the high-intensity test in the pre-test, mid-test and post-test, we specified that it consisted of a 1-min run at 20 km/h on a running platform with a 0-grade incline. Subjects were supervised throughout exercise. Vital capacity and body fat percentage were tested in only pre-test and post-test, and all tests were performed in the morning on an empty stomach to avoid any influence of diet on the test results (Forbes et al., 2020). Vital capacity was assessed using an electronic spirometer SF-1 (Jinyi, Jiangsu, China) (Guohua, 2001). The subjects inhaled deeply and then exhaled all their breath into the mouthpiece, ensuring there was no leakage, the test was performed three times, and the highest was taken. Body fat percentage was measured with the bioimpedance scale InBody 270 (Biospace, California USA),

TABLE 1 Blood lactate concentrations in the HIIT and MICT groups after high-intensity test.

Time	HIIT			MICT		
	Pre-test (mmol/L)	Mid-test (mmol/L)	Post-test (mmol/L)	Pre-test (mmol/L)	Mid-test (mmol/L)	Post-test (mmol/L)
Rest	1.91 ± 0.20	1.86 ± 0.16	1.85 ± 0.16	1.97 ± 0.16	1.91 ± 0.13	1.92 ± 0.12
Peak	14.16 ± 1.79	13.35 ± 1.00[aa]	11.81 ± 0.84[aabb]	14.65 ± 0.92	13.41 ± 0.95[aa]	12.10 ± 1.13[aabb]
0 min	14.09 ± 1.75	13.20 ± 1.23[aa]	11.70 ± 0.86[aabb]	13.98 ± 0.90	13.16 ± 1.04[aa]	11.48 ± 0.75[aabb]
5 min	12.88 ± 1.78	11.37 ± 0.68[a]	10.19 ± 1.19[aabb]	13.21 ± 1.68	11.61 ± 1.92[aa]	10.83 ± 2.05[aab]
15 min	8.70 ± 1.20	7.73 ± 0.85[aa]	5.69 ± 0.85[aabb*]	8.90 ± 1.21	8.06 ± 1.11[a]	6.55 ± 0.90[aabb]
30 min	6.39 ± 1.08	4.97 ± 0.81[aa]	2.98 ± 0.43[aabb**]	6.31 ± 0.81	5.13 ± 0.84[aa]	3.93 ± 0.71[aabb]
45 min	3.74 ± 0.70	2.82 ± 0.46[aa]	2.03 ± 0.20[aabb]	3.84 ± 0.79	2.91 ± 0.58[aa]	2.25 ± 0.30[aabb]
55 min	2.40 ± 0.49	2.01 ± 0.31[aa]	1.90 ± 0.20[aa]	2.47 ± 0.47	2.07 ± 0.26[aa]	1.96 ± 0.10[aa]

Compared to pre-test: a indicates $P< 0.05$, aa indicates $P < 0.01$; Compared to mid-test: b indicates $P < 0.05$, bb indicates $P < 0.01$; HIIT, group compared to MICT, group in the same test, *indicates $p < 0.05$, ** indicates $p < 0.01$.

ensuring that subjects were in a fasted state. To reduce bias in the assessment of the results, the two groups of subjects were mixed and performed high-intensity test together and then quietly rested to recover after the exercise. Finger peripheral blood (approx. 0.5 μL) was collected using a lactate analyzer (lactate scout, EKF Diagnostics, Cardiff, UK) immediately after test (0 min) and during the recovery period at 5 min, 15 min, 30 min, 45 min and 55 min to determine the blood lactate values at different time points, and consider the highest blood lactate value measured at several time points from 0 to 55 min as the peak value. The lactate scout (EKF Diagnostics, Cardiff, UK) is a widely utilized tool for measuring blood lactate levels (Wang J et al., 2019). It was calibrated before testing, and the fingertips were disinfected with alcohol prior to blood collection. For sampling, a disposable blood collection needle was used to puncture the subject's sterilized finger, with the first drop of blood discarded and the second drop used for testing. Blood lactate clearance percentage at each time point was calculated as the percentage of the peak lactate value, using the formula: $LA_{Time}\% = (LA_{peak} - LA_{Time})/(LA_{peak} - LA_{rest}) \times 100\%$, where LA_{peak} is the peak lactate value, LA_{Time} is the lactate value at a specific time point, and LA_{rest} is the lactate value at rest.

2.3 Statistical analysis

In this study, after excluding data from subjects who dropped out, the remaining data were tested for normality using SPSS 25.0 (Shapiro–Wilk). Two-way repeated measures analysis of variance (ANOVA) was used to explore changes in blood lactate at pre-test, mid-test, and post-test and the interaction effect of intervention cycle with intervention, and when an interaction effect was present, simple effects analyses were used to explore between-group differences. The differences in vital capacity and body fat percentage before and after the experiment were compared using ANOVA. All data are reported as the mean ± SD, and differences were considered significant at $p < 0.05$.

3 Results

3.1 Baseline indicators

The pre-test results showed that there was no significant difference in blood lactate concentration, vital capacity and body fat percentages between the HIIT and MICT groups at any measurement point. Therefore, subjects in the HIIT and MICT groups had the same basic conditions (see Table 1; Figures 1, 2).

3.2 Recovery period

The post-test results showed that blood lactate concentrations at 15 min, 30 min after test were significantly different between the HIIT and MICT groups ($p < 0.05$). Additionally, in both the HIIT and MICT groups, the post-test and mid-test blood lactate concentrations were significantly lower than the pre-test concentrations immediately to 55 min after test ($p < 0.05$). The post-test blood lactate concentrations were significantly lower than the mid-test concentrations immediately to 45 min after test ($p < 0.05$) (see Table 1).

3.3 Peak blood lactate

In both groups, post-test values were significantly lower than in mid-test and pre-test ($p < 0.05$). In tandem, mid-test was significantly lower than the pre-test ($p < 0.05$) (see Table 1).

3.4 Blood lactate clearance

Due to relatively high blood lactate values at 5 min after test (with some subjects reaching peak values at this time), and the fact that blood lactate values at 45 and 55 min after test were close to resting values (with some subjects nearing full recovery), this study

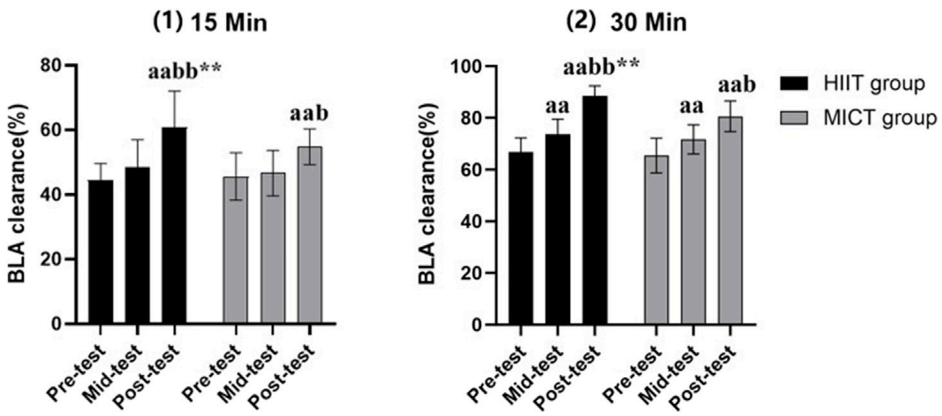

FIGURE 1
Blood lactate clearance. Compared to pre-test: a indicates $p < 0.05$, a indicates $p < 0.01$; Compared to mid-test: b indicates $p < 0.05$, bb indicates $p < 0.01$; HIIT group compared to MICT group in the same test, *indicates $p < 0.05$, ** indicates $p < 0.01$.

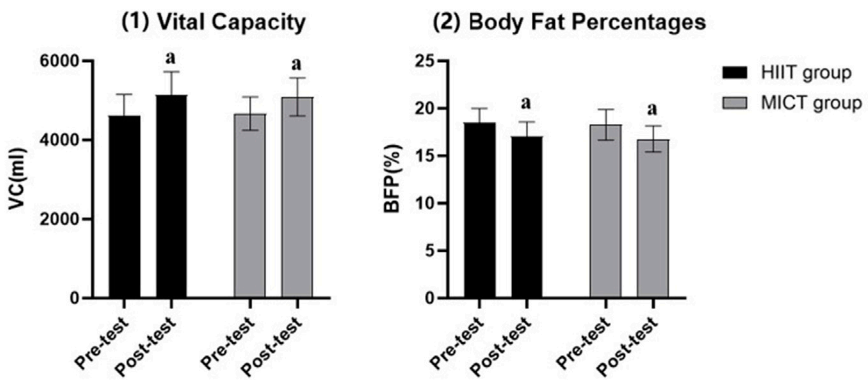

FIGURE 2
Other indicators. Compared to pre-test: a indicates $P < 0.05$.

did not calculate the blood lactate clearance percentage at these specific time points. Despite this, there was a significant difference in the percentage of blood lactate clearance at 15 min and 30 min between HIIT (15-min: 0.64 ± 0.10; 30-min: 0.89 ± 0.04) and MICT (15-min: 0.54 ± 0.04; 30-min: 0.81 ± 0.06) at post-test ($p < 0.01$). Additionally, the blood lactate clearance at 15 min and 30 min post-test in both groups was significantly higher than the pre-test (15-min HIIT:0.44 ± 0.05; 15-min MICT: 0.45 ± 0.06; 30-min HIIT: 0.67 ± 0.05; 30-min MICT: 0.65 ± 0.07) and mid-test (15-min HIIT: 0.49 ± 0.09; 15-min MICT: 0.46 ± 0.06; 30-min HIIT: 0.74 ± 0.06; 30-min MICT: 0.72 ± 0.06) ($p < 0.05$). Also, in both the HIIT and MICT groups, the 30-min blood lactate clearance in mid-test were higher than the pre-test ($p < 0.01$) (see Figure 1).

3.5 Other indicators

In terms of vital capacity and body fat percentage, the post-test (HIIT: 5147.80 ± 581.13mL/17.01% ± 1.57%; MICT: 5090.18 ± 482.51mL/16.77% ± 1.38%) of both the HIIT and MICT groups were significantly better than the pre-test (HIIT: 4595.60 ± 552.13mL/18.46% ± 1.53%; MICT: 4666.00 ± 423.53mL/18.27% ± 1.62%) ($p < 0.05$) (see Figure 2).

4 Discussion

Currently, managing exercise training load is central to sports science practice (West et al., 2021). This study provides new insights into optimizing training strategies for enhancing performance and recovery by comparing the effects of two training methods on blood lactate clearance. The results demonstrate a significant improvement in blood lactate clearance for both training conditions, with HIIT showing a more pronounced effect. This highlights the advantage of HIIT in enhancing blood lactate clearance capabilities. Additionally, this training method may also be beneficial in clinical rehabilitation, as improving lactate clearance through exercise could potentially reduce the severity of cardiovascular diseases (Li et al., 2023) or respiratory conditions (Carpenè et al., 2021).

As shown in Table 1, blood lactate concentrations in subjects generally remained at a relatively high level from immediately after the test to 5min after. Some subjects showed a "rising-declining" curve during the recovery phase (blood lactate concentration at 5 min is higher than at 0 min), which may be attributed to the delayed diffusion of muscle lactate into the blood. After lactate is produced in large quantities at the skeletal muscle site, it has to pass through the myocyte membrane into the blood to raise the blood lactate concentration. The timing of this diffusion into the blood may influence the observed changes in blood lactate levels during the recovery process (Juel and Halestrap, 1999). Since the myocyte membrane has a limiting function on the transport of lactate and the speed of transport is related to membrane permeability (Sun et al., 2017), there may be a certain time lag in the dynamic balance of the two concentrations.

The change in blood lactate concentration is influenced by several factors, including the rate of lactate production in skeletal muscle, lactate entry into the bloodstream, and lactate clearance. In our study, we attempted to interpret the results from these three perspectives. Although we were unable to separately measure lactate production and entry, we were able to indirectly assess the combined effects of these factors on lactate concentration by measuring blood lactate levels at different time points. It should be noted that our experiment primarily assessed the overall concentration changes in lactate, rather than the specific rates of production and entry. Therefore, when interpreting the results, it is essential to consider the limitations associated with these measurements.

In this study, subjects in both the HIIT and MICT groups had significantly lower blood lactate values at all time points after the intervention. Tomlin and Wenger (2001) noted that individuals with a high aerobic capacity are less dependent on anaerobic energy supply systems and are thus able to reduce the proportion of anaerobic glycolysis during exercise. It has been previously demonstrated that HIIT and MICT have a beneficial effect on the aerobic capacity of the body (MacInnis and Gibala, 2017); therefore, it can be assumed that long-term HIIT and MICT reduce the proportion of anaerobic glycolysis during a single bout of high-intensity test, which is also confirmed by the significantly lower post-test peak blood lactate than pre-test peak blood lactate observed in this study. The reasons for the decrease in the proportion of anaerobic glycolysis are mainly related to changes in the size, number, and volume of mitochondria (Holloszy and Coyle, 1984) and an increase in capillary density (Anderson and Hendriksson, 1977; Saltin and Rowell, 1980). Exercise-induced increases in the number of mitochondria facilitates an increase in the body's reliance on fat oxidation, decrease the proportion of glycolysis, and reduce lactate production (Egan and Zierath, 2013). Furthermore, an increase in capillary density is accompanied by an increase in the body's ability to supply oxygen, thereby reducing blood lactate production. But there was still controversy regarding the effects on mitochondria and capillaries in HIIT and MICT (Høier et al., 2013; Cocks et al., 2015; Martins et al., 2016) which prevented us from exploring further.

The transport and clearance of blood lactate are related to the transport capacity of the circulatory system and the density of capillaries, which increases the outflow of H^+ and blood lactate (Holloszy and Coyle, 1984). For lactate clearance, individuals with high aerobic capacity can use less energy to remove H^+ and lactate from the body during recovery, facilitating recovery (Tomlin and Wenger, 2001; Messonnier et al., 2013). From Table 1 and Figure 1, there is no difference in peak blood lactate values between the HIIT and MICT groups. However, the 15-min and 30-min blood lactate values in the HIIT group were significantly lower than those in the MICT group, and the percentage of blood lactate clearance was significantly higher than that in the MICT group. Therefore, the lower blood lactate values in the HIIT group can be attributed to the body's higher capacity for blood lactate transport and clearance.

It can be concluded that HIIT was more effective than MICT in the transport and clearance of blood lactate. Since greater disruption of homeostasis by exercise leads to a greater impact on restoring metabolism (Brehm and Gutin, 1986), we hypothesize that individuals who participate in HIIT over long periods can adapt to the acidic environment caused by lactate. They may increase their reserves of alkaline substances, allowing for quicker elimination of exercise-induced increases in blood lactate (Grgic et al., 2021). Previously, Gorostiaga et al. (1991) compared the effects of 8 weeks of continuous training (CT, exercise at 50% maximal work) and interval training (IT, exercise at 100% maximal work) on blood lactate clearance capacity, which is similar to the present study, however, the intensity of CT was lower than that of MICT. Although this study did not further explore the underlying mechanisms of the findings, but the results indicated that the intervention impact of HIIT surpassed that of MICT in improving blood lactate clearance following high-intensity test, with the disparity being more pronounced after 8 weeks compared to 4 weeks.

The HIIT group had a similar promotion effect to the MICT group in terms of vital capacity post-test indicators and this is consistent with previous studies (Martins et al., 2016; Su et al., 2019), which suggests that individuals can choose the appropriate workout to enhance vital capacity and reduce body fat percentage, based on their own preferences as well as their physical condition.

Certainly, besides running, there are other types of exercise as well, Wakayoshi et al. (1993) investigated the effects of aerobic swimming training on blood lactate concentration following high-intensity test. The results indicated a significant reduction in blood lactate levels after the intervention, which is consistent with the reduction in blood lactate response observed in the present study. This result shows that improving aerobic capacity lowers lactate response after high-intensity exercise and that various exercise forms can have similar effects. Furthermore, McMaster et al. (1989) found that swimming at 65% of maximal speed after high-intensity swimming was more effective in clearing blood lactate than passive rest. This underscores the importance of selecting appropriate training methods and recovery strategies.

5 Study limitations and future directions

As this study tested only adult males and considering that sex is also an important factor influencing the intervention (Schmitz et al., 2020; Hottenrott et al., 2021), the postintervention differences by sex could be further explored. Furthermore, as the interval duration of HIIT (Sijie et al., 2012) affects recovery, further investigation of the effect of HIIT with different intervals on lactate clearance capacity is necessary in the future. Finally, the subjects' diet is also an important factor in lactate clearance (Wang et al., 2019), the effectiveness of lactate clearance in the body can also be investigated with both diet and exercise interventions.

6 Conclusion

The results of this study show that HIIT and MICT are both effective in promoting blood lactate clearance after high-intensity test, reducing body fat and increasing vital capacity in healthy adult males, with HIIT being more effective in promoting blood lactate clearance and vital capacity. Furthermore, we do not deny the role of MICT in improving blood lactate clearance, as HIIT is not suitable for everyone. Therefore, MICT remains a valuable option, particularly for individuals who require a less intense regimen or are new to exercise. Future research should focus on the integration of these training methods into personalized fitness plans and explore their benefits across different populations to optimize exercise recommendations and improve public health outcomes.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the Ethics Committee of Beijing Normal University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. The animal study was approved by the Ethics Committee of Beijing Normal University. The study was conducted in accordance with the local legislation and institutional requirements.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Corrigendum: Effect of high-intensity interval training and moderate-intensity continuous training on blood lactate clearance after high-intensity test in adult men

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Exploring the potent enhancement effects of plyometric training on vertical jumping and sprinting ability in sports individuals

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Objective: This meta-analysis examines the impact of different combinations of plyometric training (complexity, training volume, and rest intervals) on immediate vertical jump and sprint performance in athletes.

Methods: A systematic search was conducted in four databases, and Cochrane guidelines were used to evaluate the quality of included studies. Review Manager 5.4 software was employed to analyze outcome measures. Nineteen randomized controlled trials involving 293 participants were included.

Results: Single plyometric training-induced post-activation potentiation (PAP) had a slight positive effect on vertical jump performance [SMD = −0.24, 95% CI (−0.38, −0.1), *P* = 0.0009]. Optimal results were observed with rest intervals of 0.3–4 min (SMD = 0.30, *P* = 0.0008). Sprint performance showed slight improvement [SMD = 0.27, 95% CI (0.03, 0.52), *P* = 0.03]. Complex plyometric training had a moderate effect on vertical jump performance [SMD = 0.58, 95% CI (−0.86, −0.23), *P* = 0.002], with the best outcomes seen with rest intervals exceeding 8 min (SMD = 0.77). Sprint performance also improved significantly [SMD = 0.8, 95% CI (0.01, 1.59), *P* = 0.05]. Single-session plyometric training did not significantly enhance vertical jump performance [SMD = −0.19, 95% CI (−0.41, −0.02), *P* = 0.07], but had a notable effect on sprint performance [SMD = 0.8, 95% CI (0.01, 1.59), *P* = 0.05], particularly with rest intervals exceeding 8 min (SMD = 0.77). Multiple-session plyometric training improved vertical jump (SMD = 0.43, 95% CI [0.01, 1.59), *P* = 0.00001 < 0.05], with optimal effects observed at rest intervals of 5–7 min (SMD = 0.64). Sprint performance also improved [SMD = 0.46, 95% CI (0.01, 0.81), *P* = 0.01 < 0.05].

Conclusion: Plyometric training as an activation method has significant enhancing effects, depending on training complexity, volume, and rest intervals.

KEYWORDS

plyometric training, post-activation potentiation, post-activation performance enhancement, explosive power, sprint

Introduction

Lower limb explosive strength plays a crucial role in numerous athletic disciplines and significantly contributes to enhancing sports performance (Dobbs et al., 2019; Hao et al., 2019; Zhuying et al., 2020). The ability to sprint effectively often determines the outcome of competitions during critical moments (Liang et al., 2020). The warm-up phase is a critical component for optimizing the activation of explosive muscles. An effective warm-up not only increases body temperature and reduces the viscosity of muscle fibers but also enhances the range of motion of muscles and joints, thereby minimizing muscle damage. Additionally, it activates neural excitability, leading to improved athletic performance (Sener et al., 2021).

In the 1980s, Ramsey and Street (1941) proposed the phenomenon of Post-Activation Potentiation (PAP), which refers to the sustained increase in muscle contraction force following a period of intense voluntary contraction (Botelho and Cander, 1953). This is due to the strong neural impulses generated in the cerebral cortex by high-intensity voluntary contractions, leading to the phosphorylation of myosin regulatory light chains and increased calcium sensitivity of the actomyosin complex, thereby enhancing muscle strength (Vandervoort et al., 1983; Tillin and Bishop, 2009; Seitz and Haff, 2016). PAP has become a focal point in strength training. However, improvements in performance can only be observed when the PAP level reaches its peak value (approximately 150%) after the conditioning intervention. In fact, performance improvements may occur even in the absence of PAP (Blazevich and Babault, 2019). Recently, researchers have proposed the phenomenon of Post-Activation Performance Enhancement (PAPE), which may be related to residual effects of PAP following the conditioning intervention and other factors (Cuenca-Fernández et al., 2017; Boullosa et al., 2020). While the PAP enhancement effect has a relatively short duration (It is usually less than 3 min), the peak enhancement in muscle voluntary contraction force usually occurs between 6 and 10 min after the conditioning activity (Vandervoort et al., 1983; Cuenca-Fernández et al., 2017). Therefore, researchers believe that the increase in muscle strength beyond 4 min is attributed to PAPE (Vandervoort et al., 1983; Docherty and Hodgson, 2007; Cuenca-Fernández et al., 2017; Xie et al., 2022). This suggests that PAPE is more relevant than PAP in acute performance enhancement (Blazevich and Babault, 2019). Furthermore, the improvement in muscle strength depends on the relationship between enhancement and fatigue (Rassier and Macintosh, 2000). Numerous activation methods can generate significant neural impulses (e.g., electromyographic signals) and enhance performance in activities such as jumping, throwing, and sprinting (Seitz and Haff, 2016). Methods that induce PAPE include electrical stimulation, resistance training, accentuated eccentric loading, and sprint training (Seitz and Haff, 2016).

Some studies suggest that plyometric training, as opposed to traditional resistance training, may result in higher lower limb explosive strength following activation (Hughes et al., 2016; Bridgeman et al., 2017). Plyometric training utilizes the stretch-shortening cycle (SSC) principle to improve neuromuscular function and is commonly used to enhance lower limb strength (Hakkinen et al., 1985; Fatouros et al., 2000; Markovic et al., 2007), explosiveness, and other muscle functions (Brown et al., 1986; Matavulj et al., 2001; Salonikidis and Zafeiridis, 2008; Stanley, 2017). Experimental evidence indicates that plyometric training also promotes neuromuscular adaptations and increases muscle strength (Witzke and Snow, 2000; Kato et al., 2006). However, the effectiveness is influenced by factors such as individual training experience, recovery time, and the use of additional loads during the plyometric exercises. Higher training volume and intensity can lead to greater enhancement effects and fatigue levels (Tillin and Bishop, 2009), therefore, a balance between intensity-power complex and individual characteristics, such as training volume, intensity, and rest intervals, needs to be maintained between fatigue and enhancement (Seitz and Haff, 2016).

Previous research has indicated that plyometric training has a positive effect on lower limb strength (Markovic and Mikulic, 2010; Chen et al., 2023; Saez de Villareal et al., 2023).Higher training volume and intensity can result in greater enhancement effects and fatigue levels (Tillin and Bishop, 2009). However, there is no uniform conclusion on the effects of different forms of plyometric training on sprint ability and optimal interval time. Therefore, this study aims to investigate the impact of different combinations of plyometric training (single/complex forms, single set/multiple sets) on immediate vertical jump sprint performance. We categorized the rest intervals as short (0.3–4 min), moderate (5–7 min), and long (>8 min) (Seitz and Haff, 2016). This research may be helpful for jumping or short distance sprint athletes or people with sports experience to scientifically and accurately use plyometric training to improve sports performance and avoid unnecessary fatigue, especially for athletes to use different forms and different amounts of plyometric training in season or non-season, which has important practical significance.

Methods

Search strategy

The literature search was conducted independently by two individuals using a double-blind approach, following the PICOS principles. As shown in Figure 1, four databases, namely Web of Science, PubMed, Embase, and Scopus, were searched from their inception until 9 July 2023. A mixed combination search strategy was employed, using keywords such as "post-activation potentiation," "plyometric," "stretch shortening exercise," "post-activation performance enhancement," and "PAPE" for foreign language literature. Additionally, a secondary search of the references cited in the retrieved articles was performed to maximize the inclusion of relevant literature. A total of 350 articles were identified, with 143 from Web of Science, 56 from PubMed, 53 from Embase, and 98 from Scopus. We also used JASP 0.18.3 software to perform precision-effect test and precision-effect estimate with standard errors (PET-PEESE) to quantify reported publication bias and make appropriate corrections. If the PET effect-size estimate is significant, the PEESE model, specifying a weighted least square regression predicting the effect sizes with standard errors squared, is used for publication-bias adjustment because it provides a better

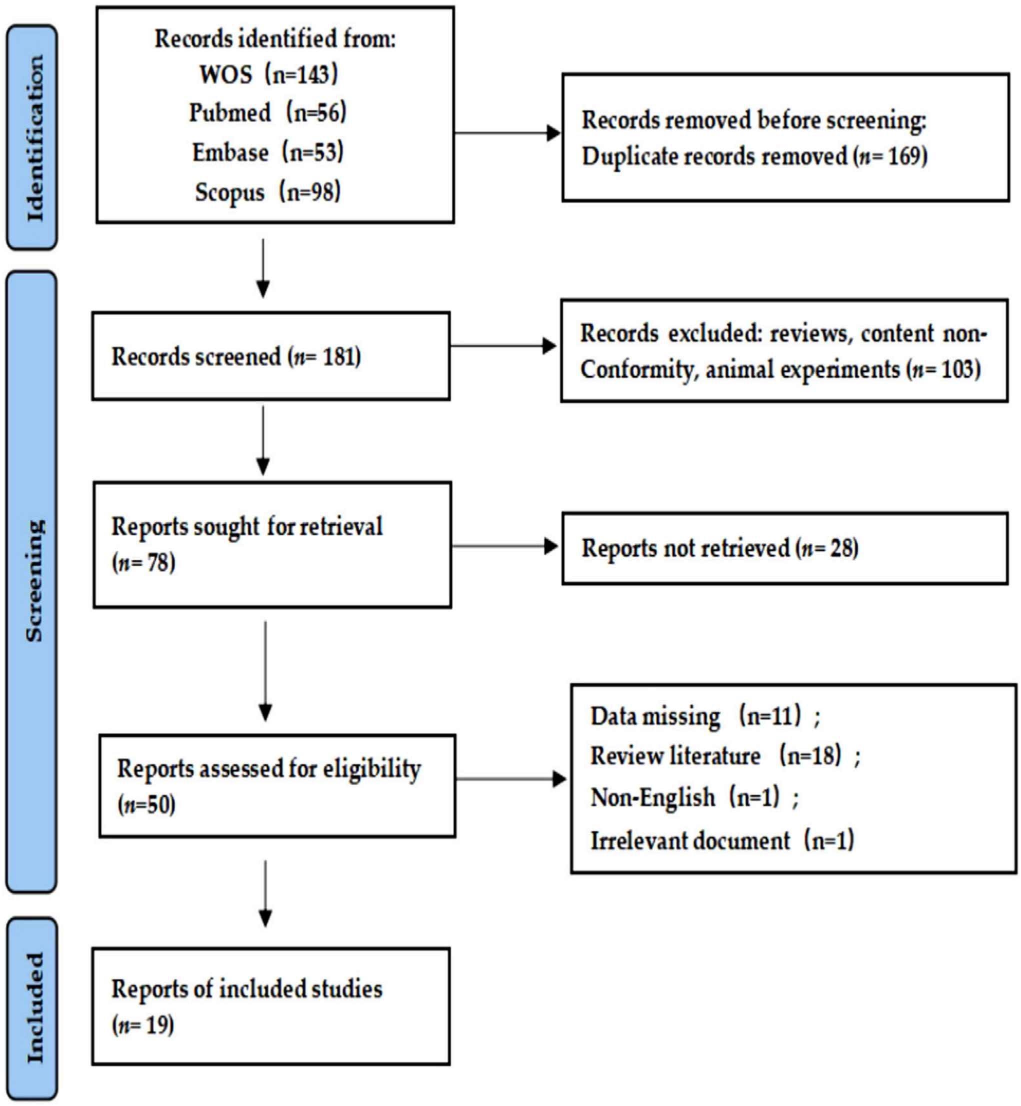

FIGURE 1
Literature screening flow chart.

effect-size approximation in the presence of an effect. If the PET effect-size estimate is not significant, the PET model and its effect-size estimate is usedAfter removing duplicate records using EndNote X9 (Bld 12062), 181 articles remained. Through the evaluation of titles and abstracts, irrelevant articles were excluded, leaving 78 articles for full-text review. After further assessment, 50 articles were deemed irrelevant, and a final set of 19 eligible articles were included for analysis.

Inclusion and exclusion criteria

Inclusion criteria

Literature Type: The included literature consisted of randomized controlled trials (RCTs). Participants: Participants were not restricted by nationality but had a minimum of 1 year of sports experience. Intervention: The intervention measure applied was post-activation potentiation (PAP) training. Outcome Measures: The outcome measures assessed were countermovement jump (CMJ) performance and 20-meter sprint times.

Exclusion criteria

Excluded literature consisted of the following: duplicate articles, review articles, interventions other than post-activation potentiation (PAP) PAPE training, studies with missing data, participants with less than 1 year of sports experience, and non-English literature. Please refer to the Figure 1 for the specific process.

Methodological quality evaluation

As shown in Figure 2 the quality of the included studies was assessed using the Cochrane Handbook for Systematic Reviews of Interventions version 5.1.0. The following criteria were

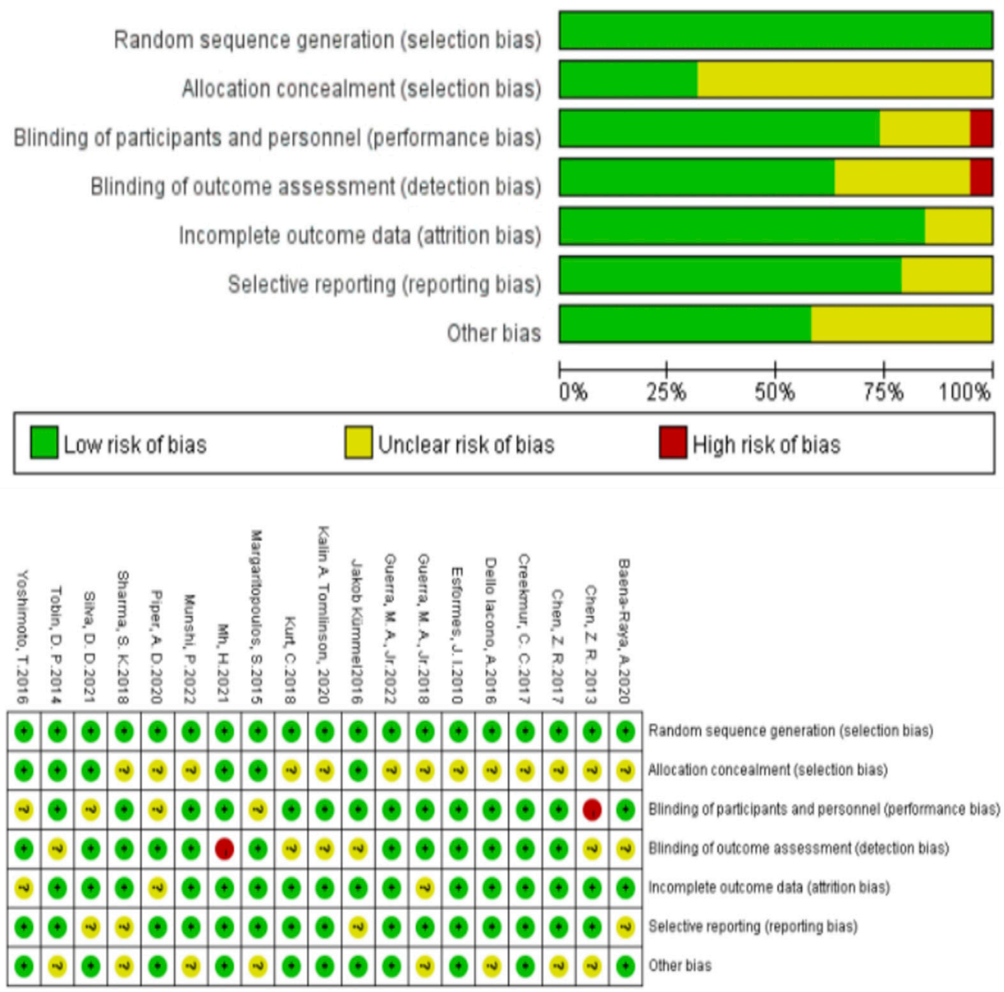

FIGURE 2
Risk bias assessment.

evaluated: random sequence generation, allocation concealment, blinding of participants and personnel, blinding of outcome assessment, selective reporting, incomplete outcome data, and other sources of bias. The risk of bias for each included study was judged as high (C), unclear (B), or low (A). The methodological quality of the studies was rated as follows: C ≤ 1, 2 ≤ B ≤ 3, A ≥ 4. Five studies included participants with different levels of physical activity (n = 338). The methodological quality of the 19 included studies was assessed using the Cochrane risk of bias tool. As shown in Table 3.

Data extraction

Two independent reviewers extracted data from the included studies using a standardized data extraction form. Data were extracted after full-text review. For data presented in graphs or figures that could not be directly extracted, the GetDate software was used. Extracted data included: first author, year of publication, sample size, participants' sport, age, potentiation intervention, potentiation load, rest interval, countermovement jump (CMJ) height, and 20-m sprint time.

Statistical processing

Data from the included studies were mostly extracted directly from the text. Review Manager 5.4 software was used to analyze the outcome measures. As the outcome measures were continuous variables, the standardized mean difference (SMD) was used as the effect size measure. The effect size was interpreted as follows: |SMD| < 0.5, small effect; 0.5 ≤ |SMD| < 0.8, moderate effect; |SMD| ≥ 0.8, large effect. Heterogeneity was assessed using the I2 statistic. I2 < 40% indicated low heterogeneity, 40% ≤ I2 ≤ 70% indicated moderate heterogeneity, and I2 > 70% indicated high heterogeneity. Fixed-effect models were used for studies with no heterogeneity or low heterogeneity, and random-effect models were used for studies with moderate or high heterogeneity. Subgroup analyses were conducted for studies with high heterogeneity.

Publication bias analysis

The impact of PAP on jump performance was reported in 19 studies. Review Manager 5.4 was used to create a funnel plot for a qualitative

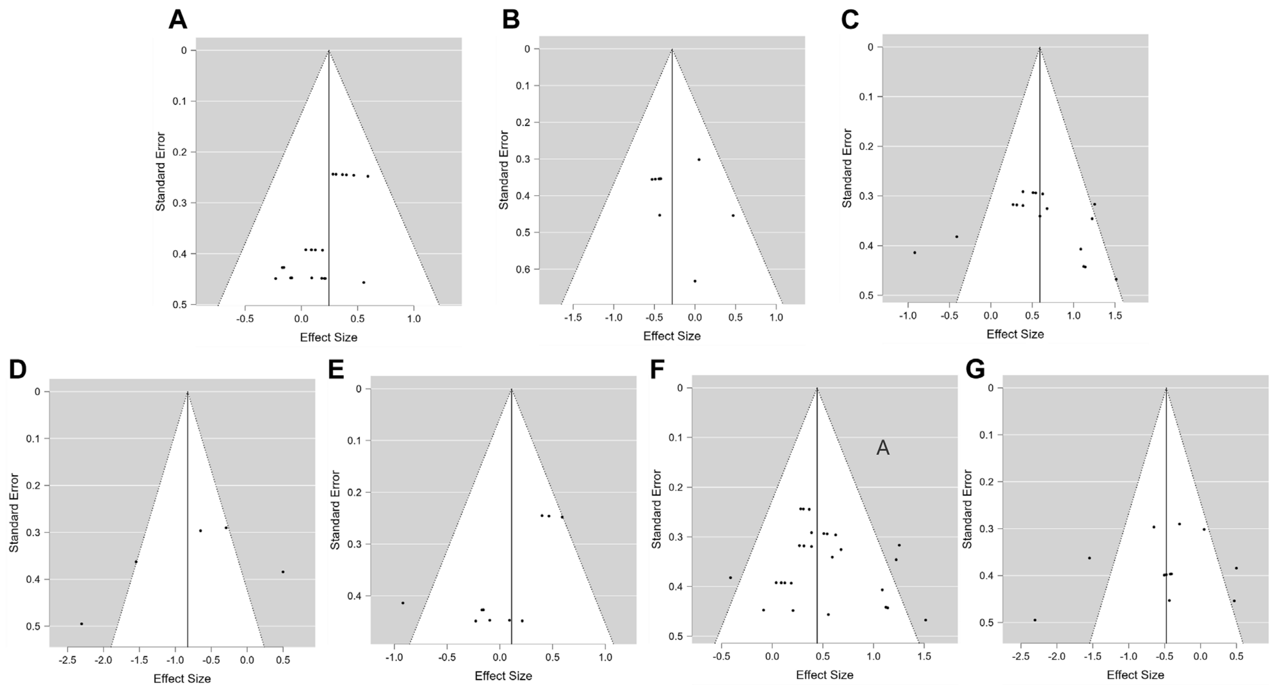

FIGURE 3
Funnel diagram of publication bias in the included literature.

analysis of publication bias in the included studies (Figure 3). The funnel plot shows that the literature points are evenly distributed on both sides of the centerline, indicating no significant publication bias.

Nineteen studies reported the effects of PAP on jump and sprint performance. Funnel plots were made using Review Manager 5.4 and Stata 15.0 to visually determine publication bias (Figure 3). The funnel plot showed that the reference points were evenly distributed on both sides of the center line, indicating no significant publication bias. To ensure scientific accuracy, we also used JASP 0.18.3 software to perform precision-effect test and precision-effect estimate with standard errors (PET-PEESE) to quantify reported publication bias and make appropriate corrections (Table 1). If the PET effect-size estimate is significant, the PEESE model, specifying a weighted least square regression predicting the effect sizes with standard errors squared, is used for publication-bias adjustment because it provides a better effect-size approximation in the presence of an effect. If the PET effect-size estimate is not significant, the PET model and its effectsize estimate is used (Stanley, 2017; Bartoš et al., 2022). As shown in Table 1, B ($P = 0.564$), C ($P = 0.702$), D ($P = 0.394$),F (0.755), G ($P = 0.482$) had no significant difference, indicating no publication bias. However, there was A significant difference between A ($P = 0.001$) and E ($P = 0.008$), indicating publication bias. PEESE corrected effect sizes were therefore used for the analysis (see Table 2).

Results

Study characteristics

Nineteen studies were included in the analysis following the PRISMA reporting guidelines, comprising a total of 19 randomized controlled trials. A total of 293 participants were included, with 163 males (55.6%), 21 females (7.2%), and 109 participants (37.2%) for whom gender was not reported. All participants had a training experience of more than 1 year and were part of the athletic population (Table 3).

Influence of different forms of plyometric training on vertical jumping and sprinting ability

Influence of single plyometrics training on vertical jumping ability

As shown in Figure 4 the data from 22 studies demonstrated the effects of single post-activation potentiation (PAP) training on vertical jump performance. Heterogeneity analysis revealed no statistical heterogeneity ($I2 = 0 \leq 40\%$, $P = 0.0009$), indicating the absence of significant heterogeneity among the studies. Therefore, a fixed-effects model was used for the meta-analysis of effect sizes, as shown in the figure. The combined effect size $|SMD| = 0.24 > 0$ indicates a small effect size, suggesting that single PAP training induces a slight improvement in vertical jump performance. [$SMD = 0.045$, 95% CI (−0.370, 0.527), $P = 0.01$].

Subgroup analysis results demonstrated that the largest effect size occurred with rest intervals of 0.3-4 min, with $|SMD| = 0.30$, $P = 0.0008$, indicating the most optimal enhancement effect. The effect size was slightly lower when the rest interval exceeded 8 min, with $|SMD| = 0.25$, indicating a mild activation effect. When the rest interval was between 5 and 7 min, the diamond symbol crossed the null line, suggesting no enhancement effect. In summary, when using single PAP training as the activation method, shorter rest intervals are more effective than longer rest intervals, while setrate rest intervals have little to no activation effect.

TABLE 1 Test of publication bias.

Project	t	Df	p
A	−4.788	20	0.001
B	0.605	7	0.564
C	−0.390	15	0.702
D	−0.993	3	0.394
E	−3.497	8	0.008
F	0.316	27	0.755
G	−0.728	11	0.482

Note: A, Influence of single plyometrics training on vertical jumping ability; B, Influence of single plyometric training on sprint ability; C, Influence of complex plyometric training on vertical jumping ability; D, Influence of complex plyometric training on sprint ability; E, Influence of Single-session plyometric training on vertical jumping ability; F, Influence of multiple plyometrics training on vertical jumping ability; G, Influence of multiple plyometrics training on sprint ability.

TABLE 2 Estimates of PEESE.

	Estimate	Standard error	t	Df	95% confidence interval		
					p	Lower	Upper
A	0.457	0.035	8.127	20	0.001	0.370	0.527
E	0.475	0.191	3.952	8	0.06	0.381	1.132

Influence of single plyometric training on sprint ability

As shown in Figure 5 the data from 9 studies demonstrated the effects of single post-activation potentiation (PAP) training on sprint performance. Heterogeneity analysis revealed no statistical heterogeneity (I^2 = 0 ≤ 40%, P = 0.03), indicating the absence of significant heterogeneity among the studies. Therefore, a fixed-effects setl was used for the meta-analysis of effect sizes, as shown in the figure. The combined effect size |SMD| = 0.27 > 0 indicates a small effect size, suggesting that single PAP training induces a slight improvement in sprint performance. [SMD = 0.27, 95% CI (0.03, 0.52), P = 0.03].

Influence of complex plyometric training on vertical jumping ability

As shown in Figure 6 the data from 17 studies demonstrated the effects of complex post-activation potentiation (PAP) training on vertical jump performance. Heterogeneity analysis revealed setrate statistical heterogeneity (I^2 = 70% > 57%>40%, P = 0.002), indicating significant heterogeneity among the studies. Therefore, a random-effects setl was used for the meta-analysis of effect sizes, as shown in the figure. The combined effect size |SMD| = 0.58 > 0.5 indicates a setrate effect size, suggesting that complex PAP training induces a slight to setrate improvement in vertical jump performance. [SMD = 0.58, 95% CI (−0.86, −0.23), P = 0.002]. However, due to the high heterogeneity, further subgroup analysis is needed.

Subgroup analysis revealed substantial heterogeneity in the studies examining the effects of PAP on vertical jump performance. The results suggest that the source of heterogeneity may be the rest intervals. Studies with longer rest intervals showed the highest homogeneity (I^2 = 0%), with the largest effect size (SMD = −0.77). Studies with setrate rest intervals (I^2 = 77%) and short rest intervals (I^2 = 48%) exhibited higher heterogeneity, with effect sizes of SMD -0.45 and −0.59, respectively. This suggests that the optimal rest interval for complex PAP training to induce the best enhancement effect on vertical jump performance is a longer interval, specifically greater than 8 min. When the rest interval exceeded 8 min, the effect size was the largest, with |SMD| = 0.77, indicating the best enhancement effect. When the rest interval was 0.3-4 min, the effect size was slightly lower, with |SMD| = 0.59, indicating a mild activation effect. When the rest interval was 5–7 min, the diamond symbol crossed the null line, suggesting no significant enhancement effect.

In summary, when using complex PAP training as the activation method, longer rest intervals are more effective than shorter rest intervals, while setrate rest intervals have little to no activation effect on vertical jump performance.

Influence of complex plyometric training on sprint ability

As shown in Figure 7 the data from 5 studies demonstrated the effects of complex post-activation potentiation (PAP) training on sprint performance. Heterogeneity analysis revealed high statistical heterogeneity (I^2 = 85% > 70%, P = 0.05), indicating significant heterogeneity among the studies. Therefore, a fixed-effects setl was used for the meta-analysis of effect sizes, as shown in the figure. The combined effect size |SMD| = 0.8 ≥ 0.8 indicates a substantial effect size, suggesting that complex PAP training induces a significant improvement in sprint performance. [SMD = 0.8, 95% CI (0.01, 1.59), P = 0.05]. However, due to the high heterogeneity, further subgroup analysis is needed.

As shown in Figure 8 the subgroup analysis results indicate that the source of heterogeneity may be the intervention method. The studies involving horizontal jump exercises within the complex

TABLE 3 Included literature information table.

Name of document	Sample size	Means of intervention	Forms of intervention		Interval time (min)			Volume (set)		Index
			Single	Complex	0.3–4	5–7	≥8	1	≥2	
Esformes et al. (2010)	13	1*6 (speed bounds + right leg speed hops + left leg speed hops + vertical bounds)		✓		5		✓		CMJ
Sharma et al. (2018)	14	2*10 (ankle hops, three sets offive hurdle hops + five drop jumps from 50 cm height)		✓	1		10		✓	CMJ, 20M
Creekmur et al. (2017)	10	2 *8 plate jumps	✓			5			✓	40M
Munshi et al. (2022)	24	5*10 (legged vertical)+2*15 m (broad jumps)+1*30 m (legged bounding) +1*5 (depth jumps)		✓	4		12		✓	CMJ, 20M
Guerra et al. (2018)	24	2*15 (ankle hops)+ 3*5 (hurdle hops)+3*20 m (sprints with sled towing)		✓	1、3	5			✓	CMJ
Tomlinson et al. (2020)	22	2*8 (loaded squat jumps) 13%	✓			5			✓	20M
Piper et al. (2020)	13	Weighted Jump of max voluntary + 10% body weight	✓		4		8、12、16、20		✓	20M\CMJ
Chen et al. (2013)	10	3*5 (drop jump height)	✓			5		✓		CMJ
Guerra et al. (2018)	12	2 *15 (ankle hops)+ 3*5 (hurdle hops)+3*20 m (sprints with sled towing)		✓	1、3	5			✓	CMJ
Dello Iacono et al. (2016)	18	3*5 (vertical or horizontal-alternate one-leg drop jumps landing from a platform 25-cm		✓			8		✓	CMJ
Tobin and Delahunt (2014)	20	2*10 (ankle hops)+3*5 (hurdle hops)+1*5 (drop jumps from a height of 50 cm)		✓	1、3	5			✓	CMJ
Mh et al. (2021)	10	2*10 (ankle hops)+3*5 (hurdle hops)+1*5 (drop jumps)	✓				10		✓	CMJ
Hamsa et al., 2021	20	2*10 (ankle hops)+3*5 (hurdle hops)+1*5 (drop jumps from 50 cm)		✓	1	5			✓	CMJ, 20M
Silva et al. (2021)	11	4 continuous single-leg vertical jump for each leg	✓		1、3		8	✓		CMJ
Kurt et al. (2018)	13	4*5 (drop jump)or 2*10 (drop jump 30 cm)	✓		2				✓	CMJ
Baena-Raya et al. (2020)	34	3*5 (drop jump) or 1*5 (drop jump 50 cm)	✓		4		8、12	✓		CMJ
Kümmel et al. ()2016	5	10 reactive hops	✓				10	✓		20M
Yoshimoto et al. (2016)	10	3*10 hurdles (height 22 cm 、 spaced 90 cm apart)	✓				10		✓	20M
Chen et al. (2013)	10	2*5 drop jump or drop jump	✓		2	6	12	✓		CMJ

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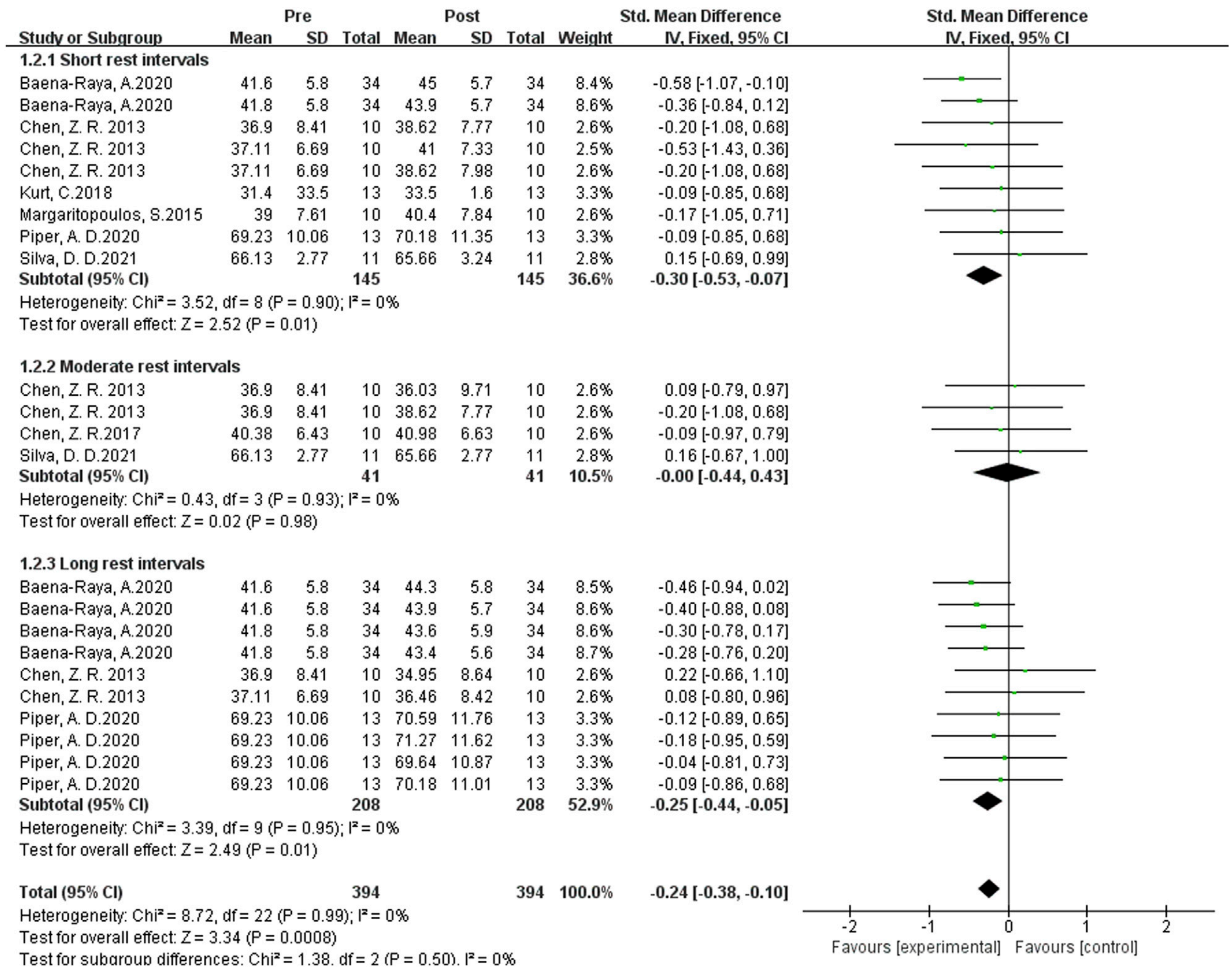

FIGURE 4
Subgroup analysis of the effects of single plyometric training on vertical jumping ability.

intervention training showed the highest homogeneity ($I^2 = 0\%$) and a setrate effect size (SMD = 0.46). On the other hand, the studies without horizontal jump exercises in the complex intervention training exhibited high homogeneity ($I^2 = 91\%$) and an effect size of SMD = 0.80. Regarding the rest intervals, whether short or long, there was high heterogeneity.

Influence of different load capacities on vertical jumping and sprinting ability

Influence of single-session plyometric training on vertical jumping ability

As shown in Figure 9 the data from 10 studies examined the effects of single-set post-activation potentiation (PAP) training on vertical jump performance. It showed low statistical heterogeneity ($I^2 = 35\% < 40\%$, P = 0.07), indicating a relatively low level of heterogeneity among the studies. Therefore, a fixed-effects setl was used for the meta-analysis of effect sizes. The diamond symbol crossed the null line, and the p-value was greater than 0.05, suggesting that single-set PAP training has no significant improvement on vertical jump performance. [SMD = −0.475, 95% CI (0.381, 1.132), P = 0.06].

Subgroup analysis examined the effects of complex PAP training on vertical jump performance. When the rest interval exceeded 8 min, the effect size was the largest with |SMD| = 0.77, indicating the best enhancement effect. When the rest interval was 0.3-4 min and 5–7 min, the diamond symbol crossed the null line, suggesting no significant enhancement effect. When the rest interval exceeded 8 min, the effect size was |SMD| = 0.34, indicating a slight improvement in vertical jump performance.

In summary, when using single-set PAP training as the activation method, only long rest intervals have an enhancement effect, while short and setrate rest intervals do not have a significant enhancement effect on vertical jump performance.

Influence of multiple plyometrics training on vertical jumping ability

As shown in Figure 10 the data from 29 studies examined the effects of complex post-activation potentiation (PAP) training on sprint performance. Heterogeneity analysis showed a high level

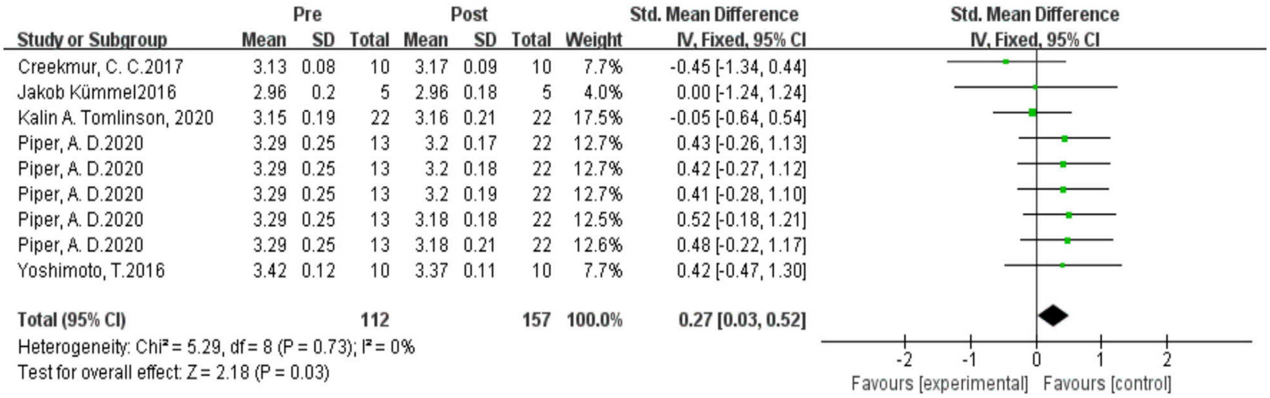

FIGURE 5
Effect of single plyometric training on sprint ability.

of statistical heterogeneity ($I^2 = 23\% \leq 40\%$, $P = 0.00001 < 0.05$), indicating significant heterogeneity among the studies. Therefore, a fixed-effects setl was used for the meta-analysis of effect sizes, as shown in the figure. The combined effect size $|SMD| = 0.43 > 0$, indicating a significant effect size, suggesting that complex PAP training induces an improvement in sprint performance. [SMD = 0.43, 95% CI (0.01, 1.59), $P = 0.00001 < 0.05$].

Subgroup analysis examined the effects of Multiple-session PAP training on sprint performance. When the rest interval was 5–7 min, the effect size was the largest with $|SMD| = 0.64$, indicating the best enhancement effect. When the rest interval was 0.3-4 min and greater than 8 min, the effect sizes were $|SMD| = 0.48$ and 0.31, respectively, indicating a slight improvement in sprint performance during these two time intervals.

In summary, when using Multiple-session PAP training as the activation method, setrate rest intervals are more effective than short rest intervals, while long rest intervals have the least activation effect on sprint performance.

Influence of multiple plyometrics training on sprint ability

As shown in Figure 11 the data from 13 studies examined the effects of Multiple-session post-activation potentiation (PAP) training on sprint performance. Heterogeneity analysis showed a high level of statistical heterogeneity ($I^2 = 66\%$, $P = 0.01 < 0.05$), indicating significant heterogeneity among the studies. Therefore, a random-effects setl was used for the meta-analysis of effect sizes, as shown in the figure. The combined effect size $|SMD| = 0.46 > 0$, indicating a significant effect size, suggesting that Multiple-session PAP training induces an improvement in sprint performance. [SMD = 0.46, 95% CI (0.01, 0.81), $P = 0.01 < 0.05$].

As shown in Figure 12 Subgroup analysis results showed that the rest interval had significant heterogeneity, and the source of heterogeneity may be the different types of enhancement interventions. Single-set training had the highest homogeneity ($I^2 = 0\%$) and the largest effect size (SMD = 0.22). Studies on multiple plyometrics training showed higher heterogeneity ($I^2 = 93\%$) with an effect size of SMD = 0.25, indicating that multiple plyometrics training has the best enhancement effect on sprint performance with longer rest intervals, specifically greater than 8 min.

Discussion

Influence of different forms of plyometric training on vertical jumping and sprinting ability

Influence of single plyometrics training on vertical jump and sprint ability

Meta-analysis results indicate that Single-session plyometric training induces a modest enhancement in vertical jump performance in athletic populations. This is consistent with the findings of (Gil et al., 2019; Gil et al., 2020). Optimal jump performance is observed with short rest intervals, followed by long intervals, while moderate intervals yield minimal improvements. The enhancement effect is influenced by two critical "windows of opportunity" (Meifu and Guo, 2019).

Post-intervention, muscle fatigue and potentiation mechanisms coexist, with their balance affecting power output and overall performance. Single-set interventions elicit a limited potentiation effect due to their singular nature. In the short term, potentiation dominates, with fatigue levels below activation levels, resulting in elevated power output during the "first window of opportunity." As rest intervals increase, the potentiation effect diminishes, fatigue becomes more pronounced, and vertical jump performance suffers. With further of rest intervals, fatigue dissipates, and the potentiation effect once again becomes dominant, leading to improved power output during the "second window of opportunity." Plyometric exercises generate elevated muscle temperatures, enhancing muscle activation and improving athletic performance, tendon tissue storage, and recoil capacity (Castro-Garrido et al., 2020; Mh et al., 2021).

Single-session plyometric training has been shown to induce modest improvements in sprint performance in athletic populations.

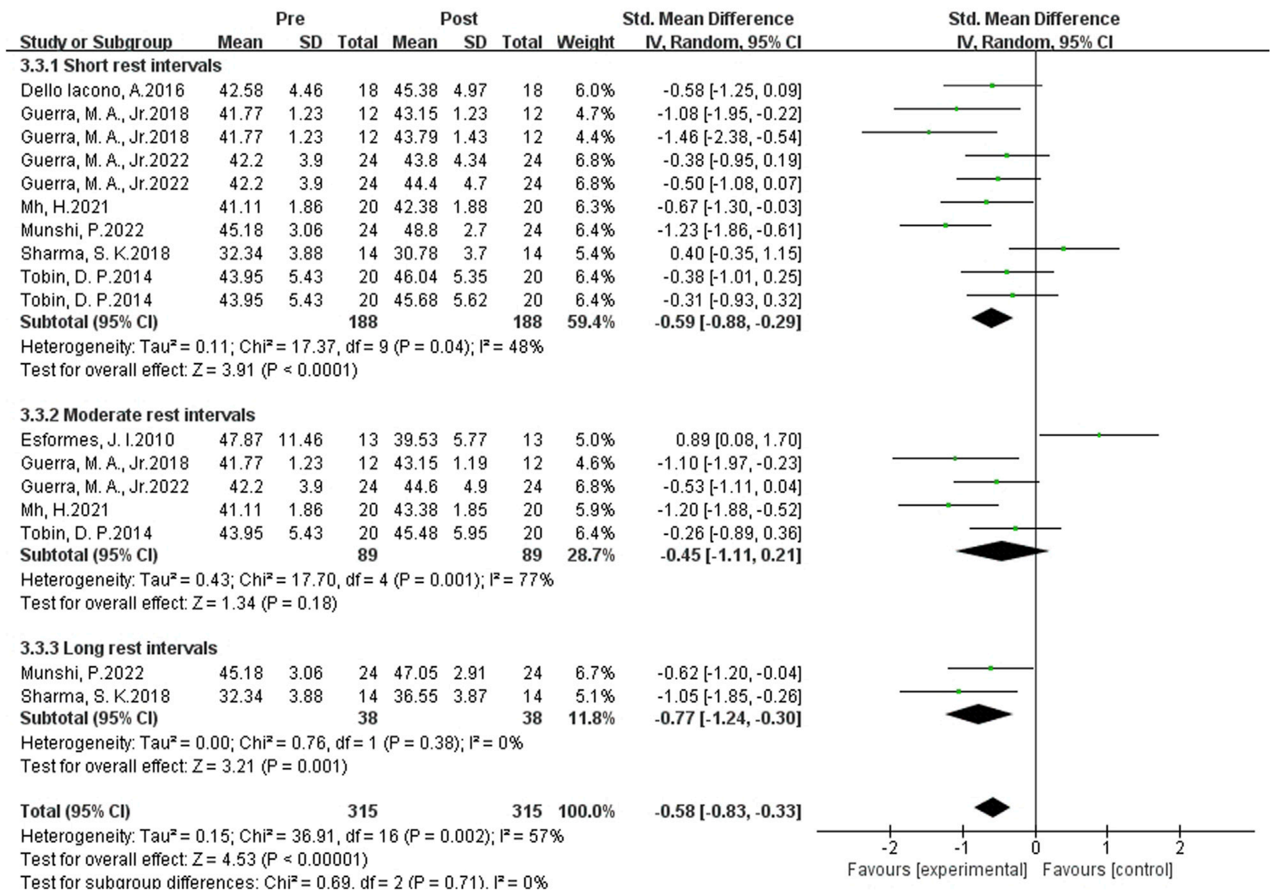

FIGURE 6
Subgroup analysis of the effects of complex plyometric training on vertical jumping ability.

Due to the relatively low stimulus of Single-session plyometric training, Creekmur et al. (2017) utilized weighted ankle jumps as a potentiating exercise. Repetitive weighted potentiated jumps elicit sufficient central nervous system stimulation to enhance sprinting ability. Research by Piper et al. (2020) has demonstrated improved sprint speeds following potentiating exercises, with 8-min and weighted potentiated exercises resulting in faster sprint times compared to 4-min protocols.

The potentiation effect elicited by longer rest intervals is greater than that of shorter intervals, as fatigue can interfere with potentiation if the PAP stimulus occurs too close to the subsequent exercise. Yoshimoto et al. (2016) study showed that high-frequency small-hurdle running improved sprint performance, possibly due to increased stride frequency, which significantly enhances velocity during the acceleration phase of sprinting. Plyometric exercises such as hurdle hopping involve horizontal potentiating jumps, with movement patterns similar to those in sprinting, thus facilitating greater positive transfer and improving sprint performance (Kümmel et al., 2016). Performing multiple repetitions of single-set potentiating jumps is an effective method to harness the PAP phenomenon, providing sufficient potentiation without inducing excessive fatigue, which can minimize unnecessary interference from complex dynamic training protocols.

Influence of complex plyometric training on vertical jumping and sprinting ability

Meta-analysis results indicate that complex plyometric training induces a significant enhancement in vertical jump performance in athletic populations. Optimal jump performance is observed with long rest intervals, followed by short intervals, while moderate intervals yield minimal improvements, which is in contrast to the effects of Single-session plyometric training on vertical jump ability. Complex plyometric training interventions are more complex and involve greater intensity, thus eliciting higher levels of fatigue.

During short rest intervals, the potentiation effect is marginally stronger than the degree of fatigue, resulting in a modest improvement in performance. As the rest interval increases, fatigue gradually diminishes, but so does the potentiation effect, with fatigue becoming more dominant and vertical jump performance suffering. With further prolongation of the interval, fatigue is nearly eliminated, while the potentiation effect persists, leading to enhanced vertical jump performance. Plyometric exercises with slightly higher intensities are more effective in improving vertical jump ability (Esformes et al., 2010; Mh et al., 2021). Complex plyometric training interventions, which include exercises such as alternate-leg hopping and single-leg hopping, further increase the intensity.

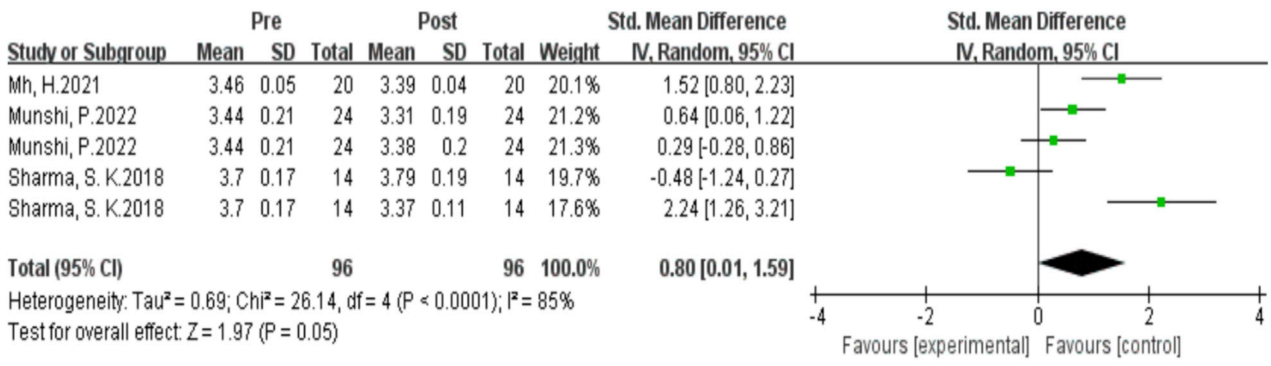

FIGURE 7
Subgroup analysis of the effect of single plyometrics training on longitudinal jumping ability

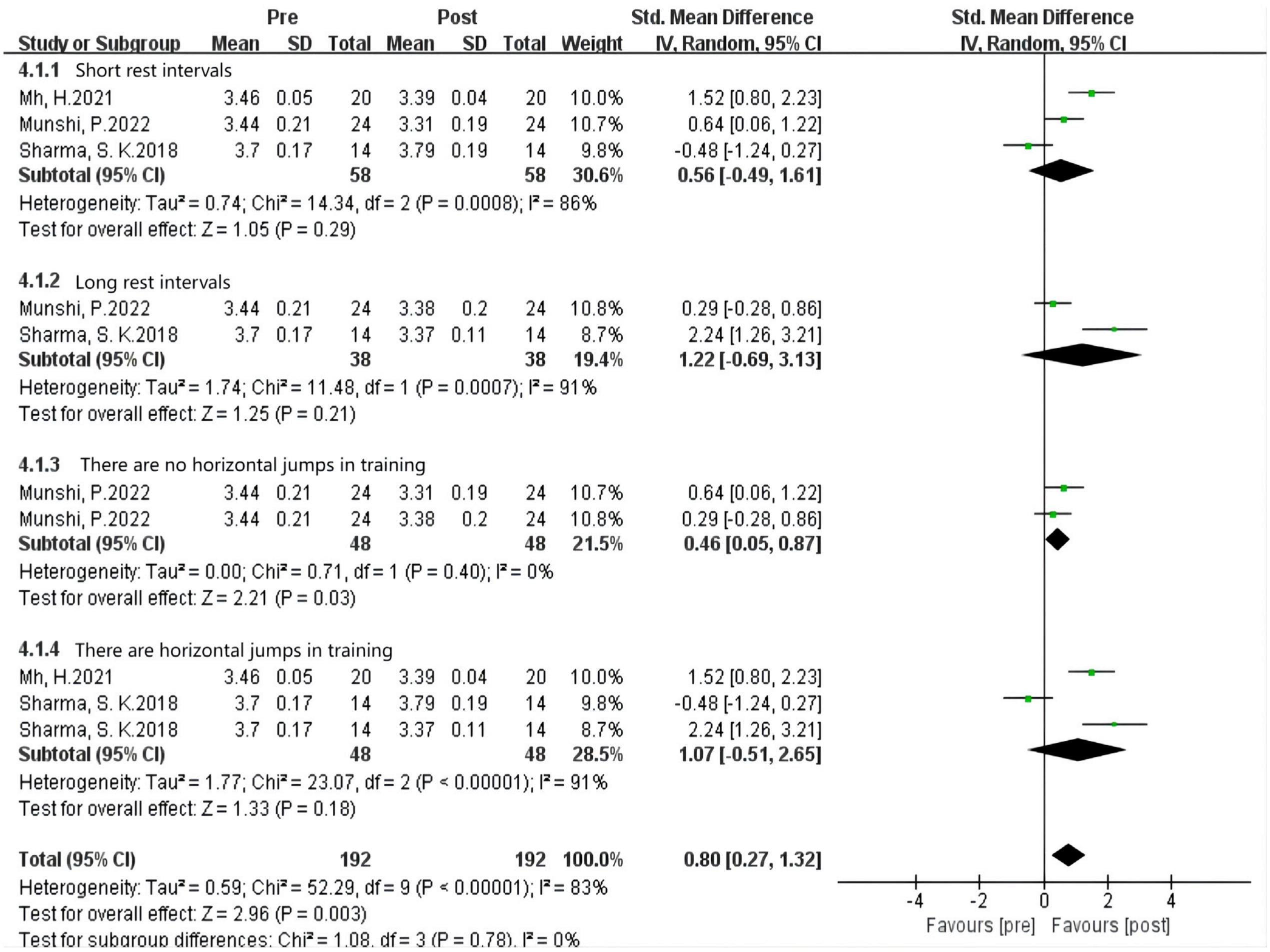

FIGURE 8
Subgroup analysis of the effects of complex plyometric training on sprint ability.

Therefore, potentiating exercises such as single-leg or alternate-leg hopping and depth jumps are more effective in enhancing vertical jump performance, and complex plyometric training protocols are superior to Single-session plyometric training, offering a more suitable option for athletes requiring reduced training volume.

Complex plyometric training induces a significant enhancement in sprint performance in athletic populations, with a larger effect size compared to Single-session plyometric training. This is likely due to the higher intensity of complex training, which further increases neural excitation and

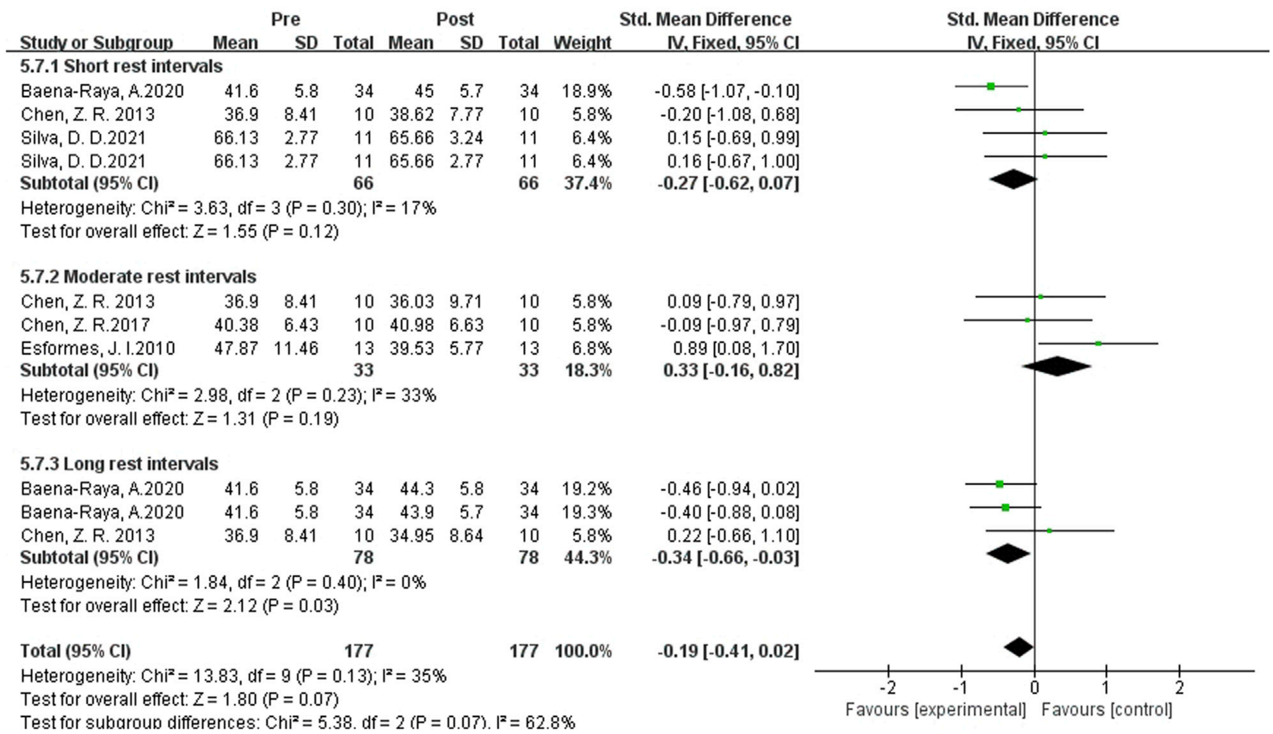

FIGURE 9
Subgroup analysis of the effects of a Single-session of plyometric training on vertical jumping ability.

potentiation. Sharma et al. (2018) study demonstrated that 20-meter sprint times were reduced 10 min after complex potentiating interventions compared to 1 min, indicating improved sprinting performance. The study also found that blood lactate levels were higher at 1 min post-intervention than at 10 min, with a corresponding decrease in 20-meter performance; however, as blood lactate decreased (at 10 min), 20-meter sprint times improved significantly. This suggests that immediately following the intervention, lactate accumulation in the blood leads to fatigue that outweighs the potentiation effect, resulting in decreased sprint performance; as the recovery period increases, lactate is broken down, fatigue is reduced, and the potentiation effect becomes dominant, leading to enhanced sprinting performance. Sharma et al.'s study showed an immediate 2.4% increase in sprint time after potentiation training, followed by an 8.9% decrease after a 10-min recovery, which is consistent with the findings of Sharma, S. K. and Mh et al. (2021). This may be related to increased phosphorylation of myosin regulatory light chains, enhanced recruitment of high-threshold motor units, and altered pennation angles (Meifu and Guo, 2019).

Subgroup analysis revealed that potentiation training interventions involving horizontal jumps resulted in superior sprint performance compared to those without horizontal jumps. This is likely because horizontal potentiating jumps generate a horizontal force vector, while vertical potentiating jumps produce minimal horizontal force, thus making the former more effective for sprint performance. From a mechanical perspective, the vertical and horizontal components of ground reaction force and the corresponding impulses are primary determinants of athletic performance. Studies have shown that horizontal jumps are more effective for increasing acceleration over short distances (less than 10 m), while vertical potentiation training is better suited for improving vertical jump performance (Tobin and Delahunt, 2014; Dello Iacono et al., 2016; Abade et al., 2017; Silva et al., 2021). The mechanism of potentiation should mimic the intended athletic performance as closely as possible to maximally stimulate the same neural pathways (Tobin and Delahunt, 2014).

Influence of different load capacities on vertical jumping and sprinting ability

Influence of single-session plyometric training on vertical jumping ability

Single-session plyometric training induces no significant enhancement in vertical jump performance in athletic populations. Subgroup analysis revealed no improvement in vertical jump performance with short and moderate rest intervals, but a slight improvement was observed with long rest intervals (George et al., 2019).

During short and moderate rest intervals, the potentiation effect elicited by Single-session plyometric training is minimal, insufficient to recruit high-threshold fast-twitch muscle fibers and enhance postsynaptic potentials, while simultaneously inducing fatigue, leading to decreased vertical jump performance (Guerra et al., 2018; Sharma et al., 2018; Baena-Raya et al., 2020). As the rest interval increases, fatigue dissipates at a faster rate than the

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Study or Subgroup	Pre Mean	Pre SD	Pre Total	Post Mean	Post SD	Post Total	Weight	Std. Mean Difference IV, Fixed, 95% CI
6.5.1 Short rest intervals								
Baena-Raya, A.2020	41.8	5.8	34	43.9	5.7	34	6.7%	-0.36 [-0.84, 0.12]
Chen, Z. R. 2013	37.11	6.69	10	41	7.33	10	1.9%	-0.53 [-1.43, 0.36]
Dello Iacono, A.2016	42.58	4.46	18	45.38	4.97	18	3.5%	-0.58 [-1.25, 0.09]
Guerra, M. A., Jr.2018	41.77	1.23	12	43.15	1.23	12	2.1%	-1.08 [-1.95, -0.22]
Guerra, M. A., Jr.2018	41.77	1.23	12	43.79	1.43	12	1.8%	-1.46 [-2.38, -0.54]
Guerra, M. A., Jr.2022	42.2	3.9	24	43.8	4.34	24	4.7%	-0.38 [-0.95, 0.19]
Guerra, M. A., Jr.2022	42.2	3.9	24	44.4	4.7	24	4.7%	-0.50 [-1.08, 0.07]
Kurt, C.2018	31.4	33.5	13	33.5	1.6	13	2.6%	-0.09 [-0.85, 0.68]
Margaritopoulos, S.2015	39	7.61	10	40.4	7.84	10	2.0%	-0.17 [-1.05, 0.71]
Mh, H.2021	41.11	1.86	20	42.38	1.88	20	3.8%	-0.67 [-1.30, -0.03]
Munshi, P.2022	45.18	3.06	24	48.8	2.7	24	4.0%	-1.23 [-1.86, -0.61]
Piper, A. D.2020	69.23	10.06	13	70.18	11.35	13	2.6%	-0.09 [-0.85, 0.68]
Sharma, S. K.2018	32.34	3.88	14	30.78	3.7	14	2.7%	0.40 [-0.35, 1.15]
Tobin, D. P.2014	43.95	5.43	20	46.04	5.35	20	3.9%	-0.38 [-1.01, 0.25]
Tobin, D. P.2014	43.95	5.43	20	45.68	5.62	20	4.0%	-0.31 [-0.93, 0.32]
Subtotal (95% CI)			**268**			**268**	**51.0%**	**-0.48 [-0.65, -0.30]**
Heterogeneity: Chi² = 20.84, df = 14 (P = 0.11); I² = 33%								
Test for overall effect: Z = 5.38 (P < 0.00001)								
6.5.2 Moderate rest intervals								
Chen, Z. R. 2013	37.11	6.69	10	38.62	7.98	10	2.0%	-0.20 [-1.08, 0.68]
Guerra, M. A., Jr.2018	41.77	1.23	12	43.15	1.19	12	2.0%	-1.10 [-1.97, -0.23]
Guerra, M. A., Jr.2022	42.2	3.9	24	44.6	4.9	24	4.6%	-0.53 [-1.11, 0.04]
Mh, H.2021	41.11	1.86	20	43.38	1.85	20	3.4%	-1.20 [-1.88, -0.52]
Tobin, D. P.2014	43.95	5.43	20	45.48	5.95	20	4.0%	-0.26 [-0.89, 0.36]
Subtotal (95% CI)			**86**			**86**	**16.0%**	**-0.64 [-0.95, -0.33]**
Heterogeneity: Chi² = 6.20, df = 4 (P = 0.18); I² = 36%								
Test for overall effect: Z = 4.01 (P < 0.0001)								
6.5.3 Long rest intervals								
Baena-Raya, A.2020	41.8	5.8	34	43.6	5.9	34	6.8%	-0.30 [-0.78, 0.17]
Baena-Raya, A.2020	41.8	5.8	34	43.4	5.6	34	6.8%	-0.28 [-0.76, 0.20]
Chen, Z. R. 2013	37.11	6.69	10	36.46	8.42	10	2.0%	0.08 [-0.80, 0.96]
Munshi, P.2022	45.18	3.06	24	47.05	2.91	24	4.6%	-0.62 [-1.20, -0.04]
Piper, A. D.2020	69.23	10.06	13	69.64	10.87	13	2.6%	-0.04 [-0.81, 0.73]
Piper, A. D.2020	69.23	10.06	13	70.18	11.01	13	2.6%	-0.09 [-0.86, 0.68]
Piper, A. D.2020	69.23	10.06	13	70.59	11.76	13	2.6%	-0.12 [-0.89, 0.65]
Piper, A. D.2020	69.23	10.06	13	71.27	11.62	13	2.6%	-0.18 [-0.95, 0.59]
Sharma, S. K.2018	32.34	3.88	14	36.55	3.87	14	2.4%	-1.05 [-1.85, -0.26]
Subtotal (95% CI)			**168**			**168**	**33.0%**	**-0.31 [-0.53, -0.09]**
Heterogeneity: Chi² = 6.34, df = 8 (P = 0.61); I² = 0%								
Test for overall effect: Z = 2.82 (P = 0.005)								
Total (95% CI)			**522**			**522**	**100.0%**	**-0.45 [-0.57, -0.32]**
Heterogeneity: Chi² = 36.43, df = 28 (P = 0.13); I² = 23%								
Test for overall effect: Z = 7.06 (P < 0.00001)								
Test for subgroup differences: Chi² = 3.05, df = 2 (P = 0.22), I² = 34.4%								

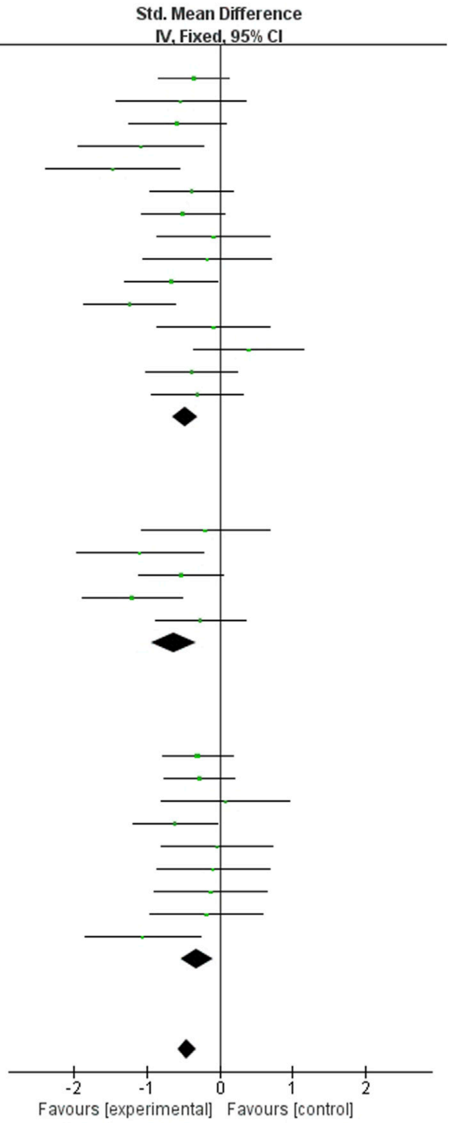

FIGURE 10
Subgroup analysis of the effects of multiple groups of plyometric training on vertical jumping ability.

Study or Subgroup	Pre Mean	Pre SD	Pre Total	Post Mean	Post SD	Post Total	Weight	Std. Mean Difference IV, Random, 95% CI
Creekmur, C. C.2017	3.13	0.08	10	3.17	0.09	10	6.7%	-0.45 [-1.34, 0.44]
Kalin A. Tomlinson, 2020	3.15	0.19	22	3.16	0.21	22	8.9%	-0.05 [-0.64, 0.54]
Mh, H.2021	3.46	0.05	20	3.39	0.04	20	8.0%	1.52 [0.80, 2.23]
Munshi, P.2022	3.44	0.21	24	3.31	0.19	24	9.0%	0.64 [0.06, 1.22]
Munshi, P.2022	3.44	0.21	24	3.38	0.2	24	9.1%	0.29 [-0.28, 0.86]
Piper, A. D.2020	3.29	0.25	13	3.18	0.21	13	7.5%	0.46 [-0.32, 1.24]
Piper, A. D.2020	3.29	0.25	13	3.2	0.17	13	7.5%	0.41 [-0.37, 1.19]
Piper, A. D.2020	3.29	0.25	13	3.2	0.18	13	7.5%	0.40 [-0.38, 1.18]
Piper, A. D.2020	3.29	0.25	13	3.2	0.19	13	7.5%	0.39 [-0.38, 1.17]
Piper, A. D.2020	3.29	0.25	13	3.18	0.18	13	7.5%	0.49 [-0.29, 1.27]
Sharma, S. K.2018	3.7	0.17	14	3.79	0.19	14	7.7%	-0.48 [-1.24, 0.27]
Sharma, S. K.2018	3.7	0.17	14	3.37	0.11	14	6.2%	2.24 [1.26, 3.21]
Yoshimoto, T.2016	3.42	0.12	10	3.37	0.11	10	6.8%	0.42 [-0.47, 1.30]
Total (95% CI)			**203**			**203**	**100.0%**	**0.46 [0.11, 0.81]**
Heterogeneity: Tau² = 0.27; Chi² = 34.89, df = 12 (P = 0.0005); I² = 66%								
Test for overall effect: Z = 2.58 (P = 0.010)								

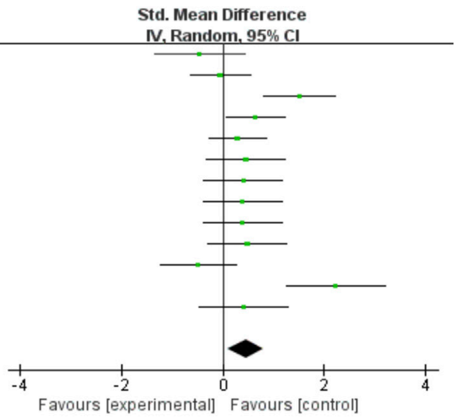

FIGURE 11
Effects of multiple plyometrics training on sprint ability.

Study or Subgroup	Pre Mean	Pre SD	Pre Total	Post Mean	Post SD	Post Total	Weight	Std. Mean Difference IV, Random, 95% CI
7.1.1 Short rest intervals								
Chen, Z. R.2017	3.29	0.25	13	3.2	0.17	13	3.9%	0.41 [-0.37, 1.19]
Guerra, M. A., Jr.2022	3.44	0.21	24	3.31	0.19	24	4.5%	0.64 [0.06, 1.22]
Mh, H.2021	3.46	0.05	20	3.39	0.04	20	4.1%	1.52 [0.80, 2.23]
Munshi, P.2022	3.13	0.08	10	3.17	0.09	10	3.6%	-0.45 [-1.34, 0.44]
Piper, A. D.2020	3.15	0.19	22	3.16	0.21	22	4.4%	-0.05 [-0.64, 0.54]
Sharma, S. K.2018	3.7	0.17	14	3.79	0.19	14	4.0%	-0.48 [-1.24, 0.27]
Yoshimoto, T.2016	3.42	0.12	10	3.37	0.11	10	3.6%	0.42 [-0.47, 1.30]
Subtotal (95% CI)			**113**			**113**	**28.1%**	**0.30 [-0.21, 0.81]**
Heterogeneity: Tau² = 0.33; Chi² = 20.83, df = 6 (P = 0.002); I² = 71%								
Test for overall effect: Z = 1.15 (P = 0.25)								
7.1.2 Long rest intervals								
Chen, Z. R.2017	3.29	0.25	13	3.2	0.18	13	3.9%	0.40 [-0.38, 1.18]
Chen, Z. R.2017	3.29	0.25	13	3.2	0.19	13	3.9%	0.39 [-0.38, 1.17]
Chen, Z. R.2017	3.29	0.25	13	3.18	0.18	13	3.9%	0.49 [-0.29, 1.27]
Chen, Z. R.2017	3.29	0.25	13	3.18	0.21	13	3.9%	0.46 [-0.32, 1.24]
Creekmur, C. C.2017	0	0	0	0	0	0		Not estimable
Guerra, M. A., Jr.2022	3.44	0.21	24	3.38	0.2	24	4.5%	0.29 [-0.28, 0.86]
Sharma, S. K.2018	3.7	0.17	14	3.37	0.11	14	3.4%	2.24 [1.26, 3.21]
Subtotal (95% CI)			**90**			**90**	**23.5%**	**0.65 [0.15, 1.14]**
Heterogeneity: Tau² = 0.23; Chi² = 12.71, df = 5 (P = 0.03); I² = 61%								
Test for overall effect: Z = 2.56 (P = 0.01)								
7.1.3 Single plyometric training								
Chen, Z. R.2017	3.29	0.25	13	3.2	0.18	13	3.9%	0.40 [-0.38, 1.18]
Chen, Z. R.2017	3.29	0.25	13	3.2	0.19	13	3.9%	0.39 [-0.38, 1.17]
Chen, Z. R.2017	3.29	0.25	13	3.18	0.18	13	3.9%	0.49 [-0.29, 1.27]
Chen, Z. R.2017	3.29	0.25	13	3.18	0.21	13	3.9%	0.46 [-0.32, 1.24]
Chen, Z. R.2017	0	0	0	0	0	0		Not estimable
Munshi, P.2022	3.13	0.08	10	3.17	0.09	10	3.6%	-0.45 [-1.34, 0.44]
Piper, A. D.2020	3.15	0.19	22	3.16	0.21	22	4.4%	-0.05 [-0.64, 0.54]
Yoshimoto, T.2016	3.42	0.12	10	3.37	0.11	10	3.6%	0.42 [-0.47, 1.30]
Subtotal (95% CI)			**94**			**94**	**27.3%**	**0.22 [-0.06, 0.51]**
Heterogeneity: Tau² = 0.00; Chi² = 4.37, df = 6 (P = 0.63); I² = 0%								
Test for overall effect: Z = 1.52 (P = 0.13)								
7.1.4 Complex plyometric training								
Guerra, M. A., Jr.2022	3.44	0.21	24	3.31	0.19	24	4.5%	0.64 [0.06, 1.22]
Guerra, M. A., Jr.2022	3.44	0.21	24	3.38	0.2	24	4.5%	0.29 [-0.28, 0.86]
Mh, H.2021	3.46	0.05	20	3.39	0.04	20	4.1%	1.52 [0.80, 2.23]
Sharma, S. K.2018	3.46	0.05	20	3.79	0.19	20	3.8%	-2.33 [-3.15, -1.51]
Sharma, S. K.2018	3.46	0.05	20	3.37	0.11	20	4.2%	1.03 [0.37, 1.70]
Subtotal (95% CI)			**108**			**108**	**21.1%**	**0.25 [-0.86, 1.35]**
Heterogeneity: Tau² = 1.47; Chi² = 56.21, df = 4 (P < 0.00001); I² = 93%								
Test for overall effect: Z = 0.44 (P = 0.66)								
Total (95% CI)			**405**			**405**	**100.0%**	**0.36 [0.07, 0.66]**
Heterogeneity: Tau² = 0.41; Chi² = 96.87, df = 24 (P < 0.00001); I² = 75%								
Test for overall effect: Z = 2.44 (P = 0.01)								
Test for subgroup differences: Chi² = 2.12, df = 3 (P = 0.55), I² = 0%								

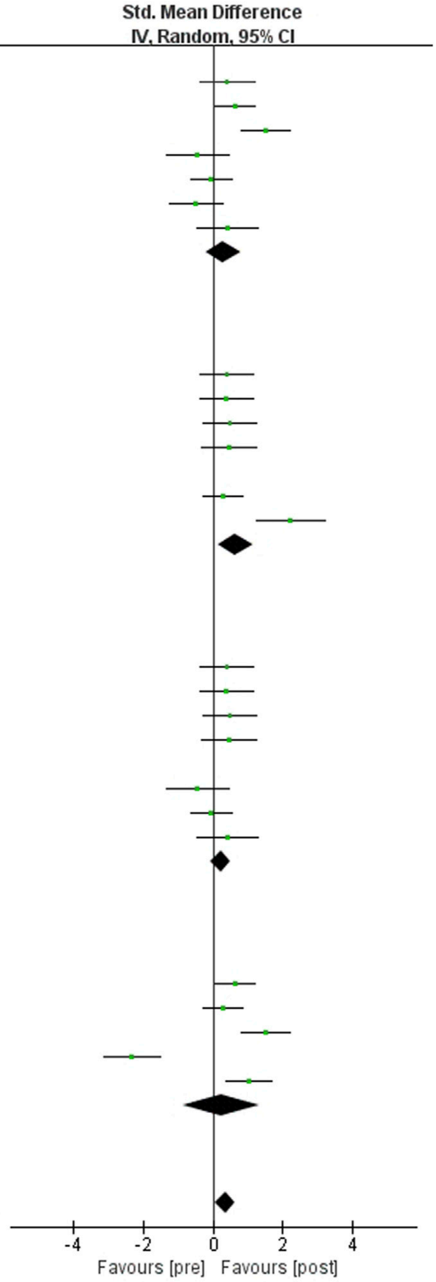

FIGURE 12
Subgroup analysis of the effects of plyometric training on sprint ability.

potentiation effect, resulting in improved vertical jump performance after long rest intervals. Single-session plyometric training, with its low training volume, does not induce PAP but rather PAPE, resulting in no improvement in vertical jump performance with short rest intervals and a slight improvement with long rest intervals. Performance enhancements (PAPE) can also occur in the absence of PAP, with peak potentiation effects occurring after longer rest intervals (Zimmermann et al., 2020). Esformes et al. (2010); Chen et al. (2013) study suggests that single-set potentiation training may not have elicited sufficiently high muscle fiber recruitment to enhance postsynaptic potentials, thereby generating an adequate potentiation effect. Vandervoort et al. (1983) study demonstrated that fatigue from muscle contractions exceeding 10 s can partially inhibit potentiation. The duration of potentiation training in Esformes, J. I.'s study was 70 s, which may have induced high levels of metabolic fatigue, interfering with the potentiation response and resulting in fatigue outweighing potentiation, thus limiting the improvement in vertical jump performance. Weighted potentiation exercises can rapidly achieve high levels of threshold motor unit activation with minimal fatigue, similar to the potentiation effect observed after high-intensity exercise, as the added weight increases the training intensity.

Increasing training intensity is necessary when employing single-set potentiation training with reduced training volume (Mh et al., 2021).

Influence of multi-group plyometric training on vertical jumping and sprinting ability

Meta-analysis results indicate that Multiple-session plyometric training significantly enhances sprint performance in athletic populations. Furthermore, the potentiation effect is most pronounced with moderate rest intervals, followed by short intervals, and least with long intervals. Previous research has shown that fatigue dissipates faster than potentiation, and athletes with higher athletic ability exhibit greater CMJ performance, possibly due to their capacity to resist fatigue or recover from it more quickly (Guerra et al., 2022). Chen et al. (2013) suggested that Multiple-session plyometric training with fewer than 3 sets can effectively induce a potentiation effect while minimizing fatigue, thereby improving vertical jump performance. Margaritopoulos et al. (2015), in his study, demonstrated that a 5-min rest interval was sufficient to induce a potentiation effect and enhance vertical jump performance in highly trained elite karate athletes. Mh, H. also reported that CMJ height was improved to a greater extent 5 min after potentiation exercises compared to 1 min.

Therefore, we speculate that the reason for these findings is that Multiple-session interventions elicit a greater potentiation effect due to the higher training load, but they also induce higher levels of fatigue. Consequently, with short rest intervals, insufficient recovery from fatigue limits the enhancement of vertical jump performance compared to moderate rest intervals (Kurt et al., 2018). With long rest intervals, although fatigue dissipates rapidly, the potentiation effect also diminishes, resulting in the least improvement. This suggests that when implementing Multiple-session plyometric training, it is crucial to avoid excessive sets and to select rest intervals that are neither too long nor too short, optimizing the timing of the potentiation effect and fatigue recovery.

Multiple-session plyometric training also significantly enhances sprint performance in athletic populations. Subgroup analysis revealed that Multiple-session plyometric training has no effect on sprint performance with short rest intervals, but it does improve sprint performance with long rest intervals. Mh, H. reported that Multiple-session weighted plyometric training can improve sprint performance; however, due to the high training load and the addition of external weight, fatigue outweighs the potentiation effect in the short term (less than 4 min) following the intervention, resulting in no improvement in sprint performance (Piper et al., 2020; Munshi et al., 2022). After a period of recovery, fatigue diminishes, and the potentiation effect becomes dominant, leading to enhanced sprint performance. Some studies have suggested that sprint speed does not improve until 3 min after Multiple-session plyometric training, gradually increases after 5 min, and can persist for up to 12 min, while isometric strength gains may persist for up to 20 min. Creekmur et al. (2017) proposed that since ankle hopping is a relatively weak stimulus, they employed repeated weighted ankle jumps (2 sets of 8 repetitions) and hypothesized that this would be sufficient to induce a potentiation effect. Their study results demonstrated that Multiple-session potentiating jumps elicit sufficient central nervous system stimulation to enhance sprint performance with longer rest intervals. Our analysis suggests that the effectiveness of Multiple-session plyometric training for improving sprint performance depends on the rest interval and training load, and it is important to optimize the timing of the potentiation effect and fatigue recovery.

Conclusion

The enhancing effects of Single plyometric training on vertical jump performance are maximized after short rest intervals, followed by long rest intervals, while there is almost no improvement after moderate rest intervals. Complex plyometric training demonstrates its greatest enhancement effect on vertical jump performance after long rest intervals, followed by short rest intervals, with no improvement observed after moderate rest intervals. Single-session plyometric training has a slight positive effect on sprinting ability, whereas the enhanced effects induced by complex plyometric training significantly improve sprinting ability.

Single-session plyometric training does not have a significant impact on vertical jump performance after short and moderate rest intervals, but it shows a slight improvement after long rest intervals. Multiple-session plyometric training has a significant enhancing effect on vertical jump performance, with the most notable enhancement observed after moderate rest intervals, followed by short rest intervals, while the effect is weakest after long rest intervals. Multiple-session plyometric training has a significant impact on sprinting ability, but there is no improvement observed after short rest intervals, while there is an improvement after long rest intervals.

Practical application

Adding plyometrics to your routine or warm-up before a race to activate your body's potential can improve performance later in the day. Plyometrics do not require complex or heavy exercise equipment, only need to overcome the body weight with your bare hands to complete. Based on the conclusions of this study, for people with training experience, we put forward the following suggestions: For the events with vertical jumping, if the training state is not good, we suggest to do 1 set of complex plyometric training and rest for 0.3–4 min before training or competition; If you feel good, do 2-4 sets of complex plyometrics and rest for 8–16 min before training or competing. For events with short sprints, we recommend 2-4 sets of complex plyometric training and 8–16 min rest if the training condition is good; If the training condition is not good, it is recommended to do 2-4 sets of single plyometric training and rest for 4–8 min before training or competition.

Research deficiencies and prospects

The subjects of this study were individuals with a certain level of sports background, and thus the conclusions may not be applicable to individuals with no history of physical activity. The literature included in this study does not differentiate between post-activation potentiation

(PAP) and post-activation performance enhancement (PAPE), which can lead to confusion when discussing the mechanisms of plyometric training on vertical jump and sprinting ability.

In future investigations of post-activation potentiation (PAP), it is advisable to utilize electromyographic systems to objectively assess its true effects. Currently, there is limited evidence regarding the effectiveness of post-activation potentiation (PAP) strategies in implementing plyometric training programs for high-level athletes. From a biomechanical perspective, the vertical and horizontal components of ground reaction forces (GRF) and their impulses are critical determinants of athletic performance. Future research should delve deeper into these aspects to design plyometric training programs in a more scientifically accurate manner.

Author contributions

LX: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Software, Writing–original draft, Writing–review and editing. JC: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Resources, Software, Writing–review and editing. JD: Data curation, Investigation, Project administration, Software, Writing–review and editing, Conceptualization, Formal Analysis, Funding acquisition, Methodology, Resources, Supervision, Validation, Visualization. WZ: Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing–review and editing. LC: Data curation, Investigation, Methodology, Software, Supervision, Writing–review and editing. JS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration,Writing–review and editing. XG: Formal Analysis, Investigation, Software, Supervision, Validation, Writing–review and editing. JS: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Writing–review and editing. HS: Conceptualization, Formal Analysis, Investigation, Software, Supervision, Validation, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2024.1435011/full#supplementary-material

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Assessing physical fitness adaptations in collegiate male soccer players through training load parameters: a two-arm randomized study on combined small-sided games and running-based high-intensity interval training

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Objective: To evaluate the effects of a 4-week intervention combining small-sided games (SSGs) and high-intensity interval training (HIIT) on physical fitness in collegiate male soccer players.

Methods: Twenty-one soccer players were randomly assigned to either the HIIT + SSGs group (n = 11) or a control group (n = 10). Physical fitness was assessed at baseline and 1-week post-intervention, including countermovement jump (CMJ), change of direction (COD) test, sprint test, repeated sprint ability (RSA) test, and 30–15 Intermittent Fitness Test (30-15IFT). The intervention comprised eight sessions over 4 weeks: four SSGs and four HIIT.

Results: The intervention group showed small to moderate improvements: mean RSA improved by 4.5% (p = 0.07), CMJ increased by 3.2% (p = 0.12), and 30–15IFT scores enhanced by 6.8% (p = 0.09). Key predictors of group membership included heart rate load per minute (OR 1.602) and various GPS variables.

Conclusion: The 4-week intervention combining SSGs with HIIT did not produce statistically significant improvements in most physical fitness variables compared to the control group. Although there were positive trends in variables such as RSA and 30-15IFT, these changes were modest and not statistically significant. The results suggest that while the combined SSGs and HIIT approach shows potential, its impact on physical fitness over a 4-week period is limited, with some variables, like CMJ, even showing decreases.

KEYWORDS

football, training load, drill-based games, physical fitness, athletic performance

Introduction

Small-sided games (SSGs) are drill-based training exercises that aim to replicate the dynamics of a real match by implementing task constraints to emphasize specific technical, tactical, and physical/physiological objectives (Davids et al., 2013; Clemente et al., 2021a). Extensive research has established SSGs as a popular and effective form of exercise for soccer players (Moran et al., 2019), providing players with a high level of physiological stimulus while engaging in dynamic drill-based activities. This approach allows coaches to integrate various stimuli and target specific tactical and technical aspects of the game (Clemente et al., 2020).

SSGs are typically categorized into three formats: small (1v1 to 4v4), medium (5v5 to 8v8), and large (9v9 to 11v11) (Owen et al., 2014). The smaller SSGs formats impose a demanding physiological stimulus, often exceeding 85% of the maximal heart rate, and place considerable mechanical work, acceleration, and deceleration demands on the players (Lacome et al., 2017). Due to the metabolic and neuromuscular benefits presented by these SSGs, this soccer-specific training mode is frequently utilized to promote maximal aerobic capacity and enhance endurance (Lacome et al., 2017). Notably, SSGs offer an appealing alternative to traditional running-based high-intensity interval training (HIIT), which is well-established for its efficacy in improving player's endurance performance, repeated sprint ability (RSA), change of direction, and achieving maximal speed in linear sprints, depending on the specific HIIT protocols employed (Clemente et al., 2021c).

Although the use of SSGs has been supported by original studies and systematic reviews as an effective method for improving endurance performance comparable to HIIT their effectiveness in enhancing change of direction, sprinting, and RSAs is not as evident (Hammami et al., 2018). This may be attributed to the limited stimulus provided in certain locomotor demands, such as high-speed running and sprint distances, due to the restricted space available for achieving high speeds during small and medium SSGs drills (Castagna et al., 2017). Moreover, the heterogeneity of these outcomes influenced by contextual factors that affect the occurrence of events requiring maximal locomotor demands, can also contribute to the lesser effectiveness of SSGs in improving change of direction, sprinting (>30 m), and repeated short sprints (<10 m) (Filipe et al., 2022).

To harness the advantages of both SSGs and HIIT, researchers have explored the potential benefits of combining these training methods in order to elicit different effects on the physical fitness of soccer players (Clemente and Sarmento, 2021). For example, a study by Harrison et al. (2015) compared a combined SSGs + HIIT (short intervals) intervention with a purely SSGs-based intervention. The results showed that players exposed to the combined format significantly increased maximal oxygen uptake compared to those only participating in SSGs. However, no significant differences were found between the groups in terms of linear sprint performance (Harrison et al., 2015). In another study that combined SSGs + HIIT (sprint interval training and repeated sprint training), no significant advantages were observed compared to SSGs alone, while the average outcomes actually favored the SSGs group (Castillo et al., 2021). Additionally, a study comparing two different combined formats (one starting with SSGs and transitioning to HIIT, and the other *vice versa*) demonstrated that both formats led to similar significant improvements in endurance performance, as assessed by the 30–15 Intermittent Fitness Test (Rabbani et al., 2019).

Despite these findings, the current body of research on the combined use of SSGs and HIIT is limited and inconsistent, highlighting the need for further investigation to obtain more robust evidence. Specifically, it is important to analyze whether a combined SSGs + HIIT approach may yield greater benefits than regular training sessions alone. This analysis should focus on the benefits for endurance performance and other important qualities such as linear sprint, change of direction, and RSA, as these are key physical attributes that can be enhanced by both SSGs and HIIT when examined independently. Additionally, considering the cumulative training load over the intervention period, establishing a dose-response relationship may help identify whether the observed adaptations in physical fitness are directly related to the imposed training program or occur independently.

Therefore, the main objectives of the current research were twofold: (i) to compare the effects of a combined SSGs + HIIT intervention *versus* a control group on measures of endurance performance, linear speed, change of direction, and RSA, and (ii) to analyze the dose-response relationship between the accumulated training load over the intervention period and the observed adaptations in male soccer player's physical fitness.

Methods

Study design

The present study employed a randomized two-arm design. Participants were recruited from a single team competing in the first division of the university championship in Taiwan. Prior to the physical fitness assessments conducted at the beginning of the experimental study, participants were randomized using an electronic-based software (Research Randomizer), utilizing a simple randomization process with 1:1 ratio. Allocation concealment was ensured as the random allocation sequence was implemented without prior knowledge of which player would receive which intervention.

Ethical procedures

All participants were provided with detailed information regarding the study design, potential risks, and benefits, and provided voluntary written informed consent to participate prior to the study commencement. The study was approved by the ethics committee of the University of Taipei (UT-IRB-2020-061). The study was conducted in adherence to the principles outlined in the Declaration of Helsinki.

Experimental approach

Participants were randomly assigned to either the intervention group or the control group. The intervention group underwent a 4-week training program consisting of additional sessions of SSGs combined with running-based HIIT training. These sessions were conducted twice a week, resulting in a total of eight sessions, with four sessions dedicated to SSGs and four sessions focusing on short-interval running. The control group followed the same field-based training as their counterparts but did not participate in the additional SSGs and running-based HIIT sessions. Physical fitness assessments were conducted at baseline (1 week prior to the intervention) and post-intervention (1 week following the 4-week intervention period). The intervention took place during the first half of the competitive season. During the experimental period, all players participated in four friendly matches.

Participants

In order to minimize the likelihood of type I statistical errors, the sample size for this study was determined using G Power 3.1.9.4 software. A power of 80% and an alpha value of 0.05 were employed in a two-tailed test to estimate the minimum number of participants needed. Drawing from the study designs of previous research (Rabbani et al., 2019) it was determined that a minimum of 11 participants in the training group would be required to minimize type I errors in the comparisons between interventions. The inclusion criteria for participant selection were as follows: 1) regular participation in soccer training at least three times per week with a minimum duration of 2 h per session, and 2) a minimum of 5 years of training experience in the sport. Exclusion criteria included: 1) any history of severe neuromuscular injury, 2) current lower extremity injury, and 3) neurological disorders. Criteria for participant withdrawal from the study included: 1) failure to attend any assessment sessions, and 2) attendance of less than 75% (less than six out of eight) of the training sessions.

Twenty-one soccer players from the first division of the university championship in Taiwan (classified as Tier 2 in the Participants Classification Framework (McKay et al., 2022), representing the Trained/Developmental level) were recruited and randomly assigned to either the SSGs + HIIT training group (n = 11; age: 17.7 ± 1.7 years; stature: 170.9 ± 5.0 cm; body mass: 61.8 ± 4.7 kg; body mass index: 21.2 ± 1.4 kg/m^2) or the control group (n = 10; age: 17.7 ± 1.8 years; stature: 170.9 ± 5.0 cm; body mass: 61.8 ± 4.7 kg; body mass index: 21.2 ± 1.4 kg/m^2). The adherence rate to the experimental group was 93.2%. Additionally, no injuries were reported throughout the duration of the study.

Training intervention

While the control group continued regular on-field soccer training practice as instructed by the coaching staff, the experimental group received an additional intervention consisting of a combination of SSGs and running-based HIIT. These sessions were conducted by the strength and conditioning coach and were completed prior to the participants' regular on-field training sessions. The details of the intervention are presented in Table 1.

Both the SSGs and running-based HIIT sessions took place on artificial turf and were conducted prior to the participants' regular on-field training sessions. During the SSGs implemented in this study, goalkeepers were not included, and the primary objective was to maintain ball possession for as long as possible via consecutive successful passing. No specific offside rules were enforced, and no verbal encouragement was provided during the games. Multiple balls were positioned along the boundaries of the pitch to facilitate immediate replacement when a ball went out of bounds.

Physical fitness assessment

The physical fitness assessments were conducted 1 week prior to the start of the intervention and 1 week following its completion. All assessments took place on the same day of the week, specifically during the first training session of the week, following a 48-h rest period after the latest match. The assessments were scheduled to begin at 4.00 p.m. The environmental conditions during the assessments were maintained at a temperature of 20oC ± 1.5°C and relative humidity of 65% ± 4%.

Prior to the assessments, a standardized warm-up protocol was performed. This protocol included a 5-min self-paced jogging exercise, followed by approximately 5 minutes of lower limb dynamic stretching exercises. Additionally, specific exercises focusing on jumping and acceleration were performed for approximately 3 min.

The sequence of the physical fitness assessments was as follows: (i) countermovement jump (CMJ), (ii) change-of-direction test, (iii) sprint test, (iv) RSA test, and (v) 30–15 Intermittent Fitness test. A rest period of 5 minutes was provided between each test to ensure adequate recovery.

Countermovement jump

The CMJ with fixed arms test was employed as a means to evaluate jump height within the scope of this particular investigation. Participants were instructed to assume an upright starting position, then flex their lower extremities and subsequently execute a jump without any pause between these phases. Throughout the jumping motion, participants were specifically directed to maintain extended knees and ensure simultaneous foot contact upon landing. Notably, the participants were instructed to fix their hands on their hips for the entirety of the

TABLE 1 Description of the experimental intervention.

Week/ Session	W1S1	W1S2	W2S1	W2S2	W3S1	W3S2	W4S1	W4S2
Sets	2	2	2	2	3	3	3	3
Reps	6	2	6	2	6	3	8	4
Reps. duration	15 s	90 s	15 s	90 s	15 s	60 s	15 s	60 s
Time between sets	4 min	4 min	4 min	4 min	4 min	4 min	4 min	4 min
Time between reps	15 s	90 s	15 s	90 s	15 s	60 s	15 s	60 s
Exercise	Short HIIT	3v3 SSGs	Short HIIT	2v2 SSGs	Short HIIT	1v1 SSGs	Short HIIT	1v1 SSGs
SSGs description	-	20 × 18 m | 60 m^2 per player	-	16 × 15 m | 60 m^2 per player	-	12 × 10 m | 60 m^2 per player	-	12 × 10 m | 60 m^2 per player
Intensity at work	90% V_{IFT}	-	100% V_{IFT}	-	95% V_{IFT}	-	100% V_{IFT}	-
Intensity between reps	Rest	Rest	Rest	Rest	Rest	Rest	Rest	Rest
Intensity between sets	65% V_{IFT}	65% V_{IFT}	65% V_{IFT}	65% V_{IFT}	65% V_{IFT}	65% V_{IFT}	65% V_{IFT}	65% V_{IFT}
Total work	6 min	6 min	6 min	6 min	9 min	10 min	12 min	12 min

W, week; m, meters; S, session; Reps, repetitions; VIFT, final velocity at 30–15 Intermittent Fitness test; HIIT, running-based high-intensity interval training; SSGs, small-sided games.

movement. To mitigate any potential unfamiliarity with the CMJ technique, participants were familiarized with the jump through prior training routines.

Countermovement jump performance was quantified using a two-axis portable force platform (PASCO, Pasport PS-2142, Roseville, USA). The force platform was utilized to measure the vertical displacement achieved during the CMJ. Participants completed three trials, each separated by a 30-s interval. The highest jump height recorded in centimeters was selected as the representative value for subsequent statistical analyses (Anicic et al., 2023).

Change of direction

The 5–0–5 test, in its original form, was utilized for this study. This test involves accelerating at maximum intensity for a distance of 10 m followed by a 5-m sprint performed at maximal intensity. Subsequently, a 180° change-of-direction (COD) maneuver is executed, followed by another 5-m maximal intensity sprint back to the starting point.

To ensure randomness and fairness, the players were randomly assigned to two groups. Half of the players commenced the trials by braking with their preferred leg at the COD line, while the remaining players initiated the trials by braking with their non-preferred leg. Each player performed three attempts using one leg before switching to the opposite leg for braking at the COD line. A rest period of 2 min was provided between each attempt to allow for adequate recovery. As the test was already a part of the team's regular assessment routines, the players were familiar with its execution and requirements. Participants completed the test wearing standard soccer boots, which are the footwear used during regular training and matches.

For the starting position, the players began 0.3 m away from the first pair of photocells (Fusion Sport, Coopers Plains, Australia), which were placed 60 cm above the ground and located at the starting line. Participants adopted a staggered stance, consistently placing the same foot in front. The best time achieved from the three trials for each foot was used as the reference measurement (expressed in seconds). From these measurements, three variables were derived: COD time, which represents the time taken to complete the test; COD deficit, which quantifies the difference between the 10-m COD time and the 10-m linear sprint time measured in the separate sprint test and COD asymmetry, that reflects the disparity between the COD times of the player's best and worst legs (with the best leg being the one with the shorter COD time) (Dos Santos et al., 2019).

Linear sprint test

The participants completed three trials of the 30-m linear sprint test. A rest period of 2 min was provided between each trial to ensure sufficient recovery. The participants were instructed to start the sprint in a staggered stance position, with their preferred foot in front. Participants were positioned 0.3 m away from the first pair of photocells, which were placed 60 cm above the ground and located at the starting line.

Three pairs of photocells were used for timing: one pair at the starting line (0 m), another pair at the 10-m mark, and a final pair at the finish line (30 m). The participants were specifically instructed to sprint as fast as possible from the starting line to the end of the 30-m track and to decelerate only after crossing the 30-m line. The split times (in seconds) for the 0–10 m and 0–30 m intervals were recorded for each trial. The best trials for the 0–10 m and

0–30 m intervals were selected for further analysis and data treatment (Altmann et al., 2019).

Repeated sprint ability (RSA)

The RSA protocol consisted of a 20-m shuttle sprint with a 20-s rest interval. The participants performed a total of six repeated sprints as part of the RSA test. To prevent pacing and ensure maximal effort, the participants were not informed of the number of sprints to be performed or the criteria for termination.

To measure the sprint time, a timing gate system (Fusion Sport, Coopers Plains, Australia) was positioned at both the starting and return lines. The players started with their preferred leg and were positioned in a staggered stance position, with their preferred foot in front. This system accurately recorded the time taken for each sprint. The following outcomes were extracted from the test results: mean RSA (the average sprint time across the six sprints performed), total RSA (the sum of the sprint times over the six sprints), best RSA (the shortest sprint time among the six sprints), worst RSA (the longest sprint time among the six sprints), and RSA decrement ([RSA total/(RSA best x number of sprints)] × 100) (Girard et al., 2011).

30–15 intermittent fitness test (IFT)

The original 30–15IFT (30–15 Intermittent Fitness Test) was utilized for this study (Buchheit et al., 2009). The test involves performing 30-s shuttle runs with 15-s walking recovery periods. The test takes place on a field measuring 40 m and is divided into three-line zones: A, B, and C. Zone B is located in the middle of the field (20 m). The 30–15IFT commences at an initial speed of 8 km/SSGs and progressively increases by 0.5 km/SSGs at each 30-s stage. The players synchronize the running pace with audio beeps provided during the test. If a player fails to sustain the required pace or does not reach the designated line zone prior to the beep on three consecutive occasions, the test is concluded. The final velocity attained during the 30–15IFT, known as VIFT (final velocity at 30–15IFT), is determined by the speed achieved in the last successfully completed stage. V_{IFT} serves as the primary outcome measure for subsequent data analysis and interpretation.

Training load monitoring

During the 4-week experimental phase of the study, both the experimental and control group participants utilized the same Global Navigation Satellite Systems (GNSS) equipment (10 Hz, Catapult playertek team, Catapult, Australia). This system incorporated a 3-dimensional accelerometer, a gyroscope, and a digital compass, which sampled data at a rate of 200 Hz. Locomotor and mechanical training demands produced by the players were monitored daily. The GNSS also integrates a heart rate monitor that allows the second-by-second heart rate responses of each player to be recorded. The system also provided a measure of heart rate load (HR load). To ensure consistent placement of the sensor, each player positioned it in the center of their chest using the specially designed elastic band provided by the company. Prior to the study, the reliability and validity of this system had been established through previous validation processes, confirming its accuracy in quantifying the most common locomotor demands.

The following physical outcomes were analyzed for each training session: total distance covered, peak speed registered, distance covered in zone 1 (Z1; 3.00–6.99 km/SSGs), distance covered in zone 2 (Z2; 7.00–10.99 km/SSGs), distance covered in zone 3 (Z3; 11.00–14.99 km/SSGs), distance covered in zone 4 (Z4; 15.00–18.99 km/SSGs), distance covered in zone 5 (Z5; 19.00 km/SSGs), time spent in deceleration zones at various rates (0–1 m/s/s, 1–2 m/s/s, 2–3 m/s/s, >4 m/s/s), number of accelerations and decelerations, maximum deceleration and acceleration experienced, work ratio, power score, impact zones of 3–5 G, distance covered in acceleration zones (0–1 m/s/s, 1–2 m/s/s, 2–3 m/s/s), time spent in acceleration zones (1–2 m/s/s, 2–3 m/s/s), and distance covered in power zones (0–5 SSGs/kg, 15–20 SSGs/kg, 25–30 SSGs/kg, 30–35 SSGs/kg, >50 SSGs/kg).

In addition to the use of sensors for monitoring physical exertion, the rate of perceived exertion (RPE) was also assessed using Foster's 10-point scale (Foster et al., 2001). This scale allows individuals to subjectively rate the perceived level of exertion during training sessions. To calculate the session-RPE, the score provided at the end of the training session is multiplied by the duration of the session in minutes.

The RPE assessments were conducted individually, approximately 30 min following the completion of each training session. Participants were familiarized with the RPE scale prior to the study as it is commonly employed as part of the team's regular training/monitoring routines. The RPE data were recorded in an Excel spreadsheet for further analysis.

Statistical procedures

For statistical analysis, 2-way repeated measures ANOVA with a between and within-subjects design was used for the fitness variables. Prior to the commencement of the analysis, the Shapiro-Wilks normality test was carried out and established the normal distribution of the sample. Moreover, the Box's test assumption for the equality of variance-covariance matrices of difference scores between groups was achieved.

To present the findings, mean values were reported along with their corresponding standard deviations (mean ± SD). Descriptive statistics were conducted for all variables to provide a comprehensive characteristic summary. In addition, Cohen's d effect size analysis was employed to examine the magnitude of differences within the study sample which was evaluated using the Hopkins scale as follows: 0–0.2, trivial; 0.2–0.6, small; 0.6–1.2, moderate; 1.2–2.0, large; >2.0, very large (Cohen, 1988). To determine statistical significance, the level of significance was set at $p < 0.05$. SPSS Statistical Software v.24.0, Spyder v3.6.6, Python (v3.7) IDE, and its associated scikit-learn libraries, coupled with Jamovi Version 2.3 (The Jamovi Project 2022) were utilized for the statistical analyzes, which facilitated data processing and computations.

Identifying relevant GPS variables

Extremely Randomized Trees (ERT) is a tree-based ensemble technique used for supervised classification and regression problems. It is a variant of Random Forests that constructs decision trees by utilizing random thresholds for each feature and selecting the most appropriate feature among a random subset of features at each node. Numerous studies have demonstrated that ERT yields more precise results than other approaches such as Support Vector Machines (SVM) and Random Forests (Geurts and Wehenkel, 2000; Geurts et al., 2006). Extremely Randomized Trees is ideal over other methods for feature extraction due to its capability of handling high-dimensional data consisting of multiple features. Due to the high dimensionality of the GPS dataset in the present investigation, ERT was employed to identify the essential GPS parameters that are relevant to the groups of examined players.

Cluster analysis for defining player load

K-means clustering is a widely adopted unsupervised machine learning algorithm that is utilized to classify data points into clusters or groups according to their similarity The algorithm partitions the data into k clusters specified by the user. Each data point is then assigned to the closest cluster center and updated the cluster centers are based on the mean of the data points allocated to each cluster (Muazu Musa et al., 2019). The algorithm proceeds with this iterative process until a state of convergence is attained. In the context of this study, k-means clustering was employed to categorize the cumulative load that the players were subjected to during the intervention period.

Model development for understanding dose-response relationships among the GPS study variables

A dose-response-based model of performance was created by using a multivariate binary logistic regression. The impact of each variable on the group of player's performances was determined, and the magnitude of the changes in the variables was predicted. In this analysis, the independent variables were the variables identified via the ERT selection method, while the group of players, i.e., control and experimental, served as the dependent variables. The levels of players' load identified through the k-mean clustering were introduced to the model as a covariate to test the predictive ability of the model while accounting for the effect of different loads exposed to the players. This technique is useful in identifying the most significant variables that could differentiate the group of players concerning the specific training they receive during the intervention period. The Forward stepwise selection method (Likelihood Ratio) was employed to analyze the data. The results were reported in terms of odds ratios (OR) and 95% confidence intervals (CI). Nagelkerke's R^2 was used to evaluate the model's explanatory power, with the effect size interpreted as small (0.02–0.13), medium (0.13–0.26), and large (>0.26). The model's goodness of fit was assessed using the Hosmer-Lemeshow test, and the discriminant capacity of the model was evaluated using the area under the curve (AUC) and the Receiver Operating Characteristic (ROC) curve, which was generated using the predicted probabilities for each variable.

Results

Analysis of between subjects-effects

No statistical significance differences were observed between groups for any of the examined fitness variables. However, despite the lack of significant difference between the two groups, it was observed that the experimental group (SSGs + HIIT) recorded a noteworthy improvement in certain fitness levels during post-intervention compared to the control group (Table 2). These fitness variables consist of asymmetry index (% change = 46.9, Cohen's d = 0.33), mean RSA (% change = 3.8, Cohen's d = 0.55), worse RSA (% change = 3.7, Cohen's d = 0.43), CMJ (% change = −2.7, Cohen's d = 0.35) and the 30–15IFT (% change = 8.8, Cohen's d = 0.41).

Analysis of within subject-effects and time interactions

As shown in Table 2, significant interactions were observed across 10 fitness variables. The main effect of time on resting heart rate was significant in the control group ($p < 0.05$) but not in the experimental group ($p > 0.05$). For left change of direction, significant effects were found across all groups ($p < 0.001$) and within the experimental group ($p < 0.001$). Significant interactions of time and within-group performance were noted for the right change of direction across groups ($p < 0.05$) and for the best change of direction ($p < 0.001$). The asymmetry index showed significant changes in the control group ($p < 0.05$) but not in the experimental group ($p > 0.05$). Main effects of time and within-group interactions for COD deficit were significant across all groups ($p < 0.001$). For the experimental group, changes in mean, total, and best RSA were significant ($p < 0.05$), while no significant changes were observed in the control group ($p > 0.05$). Finally, changes in the 30–15IFT were significant for the experimental group ($p < 0.001$) but not for the control group ($p > 0.05$).

Figures 1, 2 display the variation of groups for the different outcomes, considering the within-player variation.

Figure 3 illustrates the ERT technique results, identifying the 10 most important variables out of 93 initially gathered. These variables are crucial for player performance across both groups and were used to develop the logistic regression model. Descriptive statistics for the remaining non-essential variables are available in Supplementary Appendix S1.

Figure 4 shows the k-means clustering analysis of players' load, identifying three categories: low, moderate, and high. The mean loads for these categories were 46.71, 101.66, and 201.36, respectively. These load levels were used as covariates in model building.

Table 3 shows the multivariable binary logistic regression model assessing GPS variables for predicting changes between the two

TABLE 2 Inferential and descriptive statistics of the fitness variables.

Variables	SSGs + HIIT (n = 11)			Control group (n = 10)			Between group (baseline)	Between group (post intervention)
	Baseline	Post-intervention	Within group	Baseline	Post-intervention	Within group		
Resting heart rate (bpm)	70.818 ± 13.636	75.909 ± 10.568	$F = 1.20$; $p = 0.299$; $\eta^2_p = 0.107$	71.39 ± 214	76.7 ± 5.945[aa]	$F = 6.83$; $p < 0.05$*; $\eta^2_p = 0.431$	t = 0.093; $p = 0.926$; d = 0.041	t = 0.208; $p = 0.837$; d = 0.091
% Change	+7.2		N/A	+7.4		N/A	N/A	N/A
Sprint 10 m (s)	1.824 ± 0.099	1.785 ± 0.0688	$F = 1.57$; $p = 0.239$; $\eta^2_p = 0.136$	1.833 ± 0.068	1.825 ± 0.075	F = 1.10; $p = 0.321$; $\eta^2 p = 0.109$	t = 0.248; $p = 0.807$; d = 0.108	t = 0.777; $p = 0.447$; d = 0.339
% Change	−2.1		N/A	−0.44		N/A	N/A	N/A
30-m linear sprint (s)	4.293 ± 0.137	4.299 ± 0.137	$F = 5.21$; $p = 1.000$; $\eta^2_p = 0.001$	4.346 ± 0.119	4.336 ± 0.210	$F = 0.043$; $p = 0.839$; $\eta^2_p = 0.005$	t = 0.941; $p = 0.359$; d = 0.411	t = 0.536; $p = 0.598$; d = 0.234
% Change	+0.14		N/A	−0.23		N/A	N/A	N/A
Left COD 5-0–5 test (s)	2.239 ± 0.053	2.330 ± 0.097[aa]	$F = 29.4$; $p < 0.001$*; $\eta^2_p = 0.746$	2.236 ± 0.101	2.374 ± 0.136[aa]	$F = 48.2$; $p < 0.001$*; $\eta^2_p = 0.843$	t = - 0.088; $p = 0.930$; d = - 0.038	t = 0.858; $p = 0.402$; d = 0.375
% Change	+4.1		N/A	+6.2		N/A	N/A	N/A
Right COD 5-0–5 test (s)	2.263 ± 0.0618	2.336 ± 0.111[a]	$F = 6.37$; $p < 0.05$*; $\eta^2_p = 0.389$	2.298 ± 0.068	2.378 ± 0.109[a]	$F = 6.74$; $p < 0.05$*; $\eta^2_p = 0.428$	t = 1.238; $p = 0.231$; d = 0.541	t = 0.863; $p = 0.399$; d = 0.377
% Change	+3.2		N/A	+3.5		N/A	N/A	N/A
Best COD time (s)	2.230 ± 0.055	2.301 ± 0.078[aa]	$F = 26.5$; $p < 0.001$*; $\eta^2_p = 0.726$	2.230 ± 0.09	2.353 ± 0.130[aa]	$F = 33.0$; $p < 0.001$*; $\eta^2_p = 0.786$	t = 0.001; $p = 1.000$; d = 0.001	t = 1.125; $p = 0.275$; d = 0.491
% Change	+3.2		N/A	+5.5		N/A	N/A	N/A
Asymmetry index COD (s)	1.889 ± 1.506	2.775 ± 2.422	$F = 0.941$; $p = 0.0941$; $\eta^2_p = 0.086$	3.397 ± 2.620	2.017 ± 2.123[a]	$F = 13.7$; $p < 0.005$*; $\eta^2_p = 0.603$	t = - 1.637; $p = 0.118$; d = - 0.715	t = 0.758; $p = 0.457$; d = 0.331
% Change	+46.9		N/A	−40.6		N/A	N/A	N/A
COD deficit (s)	0.406 ± 0.117	0.516 ± 0.090[a]	$F = 8.26$; $p < 0.01$*; $\eta^2_p = 0.452$	0.397 ± 0.089	0.544 ± 0.130[aa]	$F = 25.0$; $p < 0.001$*; $\eta^2_p = 0.735$	t = - 0.206; $p = 0.841$; d = - 0.089	t = 0.569; $p = 0.576$; d = 0.249
% Change	+27.1		N/A	+37.0		N/A	N/A	N/A
Mean repeated sprint ability (s)	7.937 ± 0.292	8.239 ± 0.458[a]	$F = 7.57$; $p < 0.05$*; $\eta^2_p = 0.431$	7.835 ± 0.383	7.942 ± 0.624	$F = 1.04$; $p = 0.335$; $\eta^2_p = 0.103$	t = −0.689; $p = 0.499$; d = - 0.301	t = −1.253; $p = 0.225$; d = −0.547
% Change	+3.8		N/A	+1.4		N/A	N/A	N/A
Total RSA (s)	46.911 ± 3.105	48.714 ± 4.020[a]	$F = 7.45$; $p < 0.05$*; $\eta^2_p = 0.427$	45.511 ± 5.872	46.874 ± 4.675	$F = 0.611$; $p = 0.454$; $\eta^2_p = 0.064$	t = −0.692; $p = 0.497$ days = - 0.302	t = −0.969; $p = 0.345$; d = −0.423
% Change	+3.8		N/A	+3.0		N/A	N/A	N/A
Best RSA (s)	7.494 ± 0.365	7.857 ± 0.404[a]	$F = 7.65$; $p < 0.05$*; $\eta^2_p = 0.434$	7.419 ± 0.247	7.565 ± 0.488	$F = 1.72$; $p = 0.222$; $\eta^2_p = 0.161$	t = −0.541; $p = 0.594$ days = -0.236	t = −1.499; $p = 0.150$; d = −0.655
% Change	+4.8		N/A	+2.0		N/A	N/A	N/A
Worst RSA (s)	8.311 ± 0.295	8.617 ± 0.555	$F = 3.94$; $p = 0.075$; $\eta^2_p = 0.283$	8.139 ± 0.430	8.321 ± 0.801	$F = 1.47$; $p = 0.256$; $\eta^2_p = 0.141$	t = −1.076; $p = 0.295$ days = - 0.470	t = −0.992; $p = 0.333$; d = −0.433
% Change	+3.7		N/A	+2.2		N/A	N/A	N/A

(Continued on following page)

TABLE 2 (*Continued*) Inferential and descriptive statistics of the fitness variables.

Variables	SSGs + HIIT (n = 11)			Control group (n = 10)			Between group (baseline)	Between group (post intervention)
	Baseline	Post-intervention	Within group	Baseline	Post-intervention	Within group		
RSA decrement (s)	4.380 ± 5.752	3.294 ± 6.136	*F* = 0.644; *p* = 0.441; η^2_p = 0.060	2.111 ± 11.760	3.169 ± 5.952	*F* = 0.061; *p* = 0.809; $\eta^2 p$ = 0.007	t = 0.570; *p* = 0.575 days = - 0.249	t = −0.047; *p* = 0.963; d = −0.020
% Change	−24.8		N/A	+50.1		N/A	N/A	N/A
CMJ (cm)	40.889 ± 5.804	39.786 ± 4.760	*F* = 1.44; *p* = 0.258; η^2_p = 0.126	40.209 ± 5.093	37.809 ± 6.343	*F* = 3.91; *p* = 0.079; η^2_p = 0.303	t = -0.284; *p* = 0.779 days = − 0.124	t = −0.813; *p* = 0.426; d = - 0.355
% Change	−2.7		N/A	−6.0		N/A	N/A	N/A
30–15 IFT test (km)	18.636 ± 0.977	20.273 ± 1.232[aa]	*F* = 21.0; *p* < 0.001*; η^2_p = 0.677	19.000 ± 1.269	19.700 ± 1.531	*F* = 4.85; *p* = 0.055; η^2_p = 0.350	t = 0.739; *p* = 0.468 days = - 0.323	t = −0.948; *p* = 0.355; d = −0.414
% Change	+8.8		N/A	+3.7		N/A	N/A	N/A

Notes: a: Significant interactions over time (*p* < 0.05).
aa: Significant interactions over time (*p* < 0.001).
*: Significant different within player variation.
N/A: not applicable.

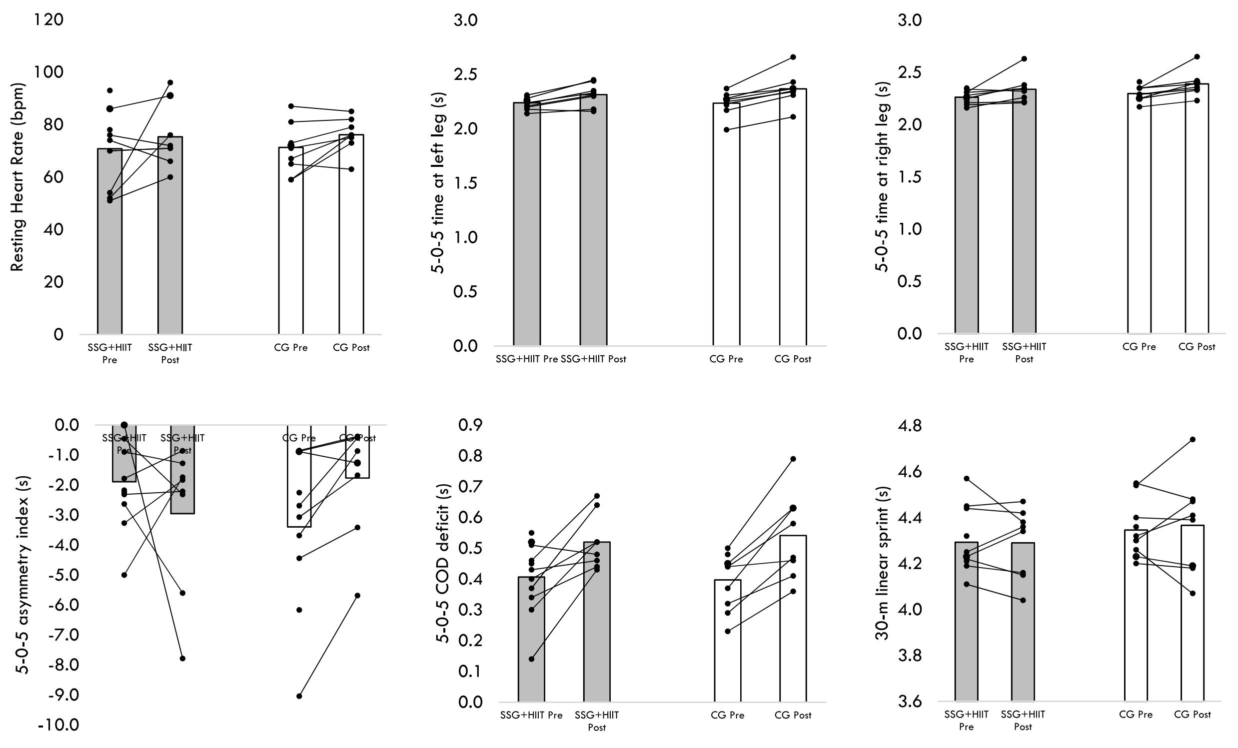

FIGURE 1
Variations of both groups in resting heart rate, 30-m linear sprint and 5-0-5 test performance.

player groups. The model had good fit (Hosmer-Lemeshow >.05), classification accuracy (68%), and discriminant capacity (AUC 76%). It explained 26% of the variance (Negelkerke R^2 = 0.26). Seven key variables were significant in predicting group membership ($p < 0.05$): heart rate load per minute, time in speed zone 2 (secs), impact zones 3-5G, maximum deceleration, time in acceleration zones 1–2 m/s^2 (secs), distance in power zone 0–5 SSGs/kg (m), and distance in power zone 10–15 SSGs/kg (m).

Odds ratios showed that the experimental group had a 60% higher chance of increased heart rate load per minute (OR 1.602)

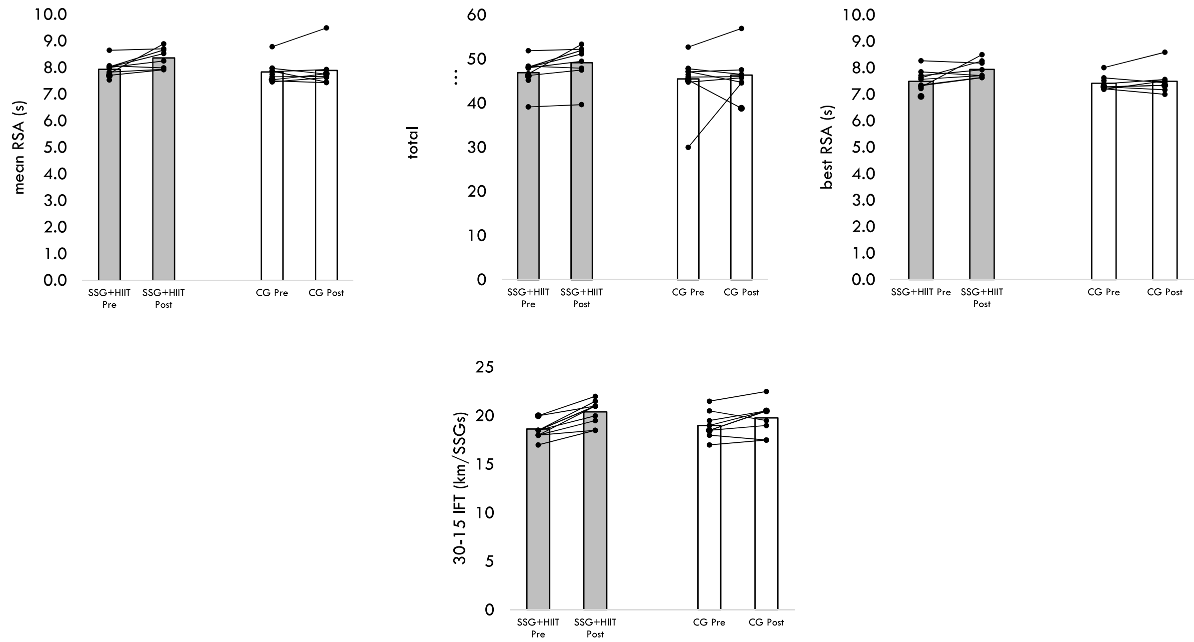

FIGURE 2
Variations of both groups in repeated sprint ability test and the 30-15 Intermittent Fitness test performances.

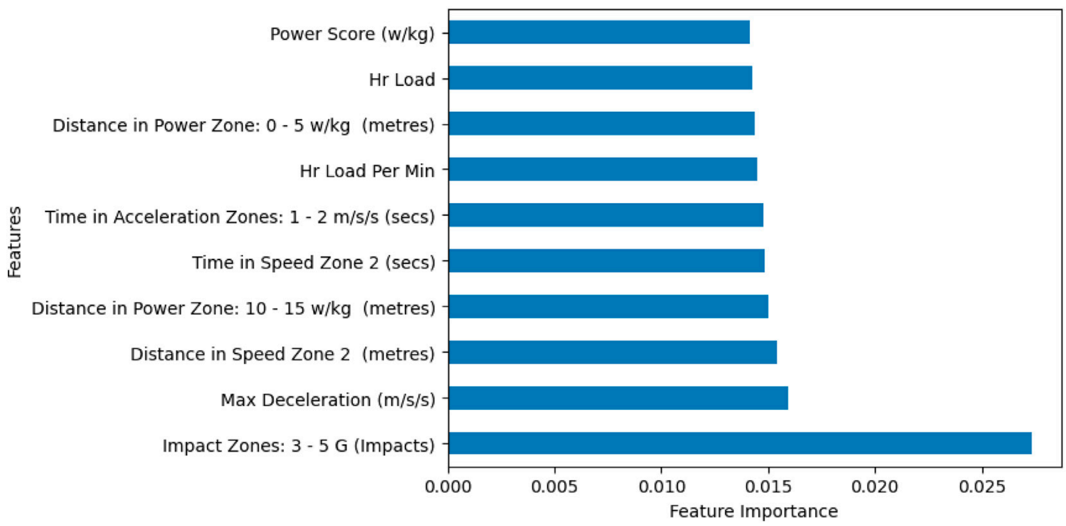

FIGURE 3
Relevant and essential GPS variables results based on extremely randomized tree analysis.

and a 0.4% lower chance of spending time in speed zone 2 s (OR 0.996). The control group had a 1.3% higher probability of decreased impact zones 3-5G (OR 0.987) and a 10% higher chance of reduced maximum deceleration (OR 0.989). For each unit increase in time in acceleration zones 1–2 m/s^2, the control group had a 4.9% higher likelihood of decreased maximum acceleration. The experimental group was 0.5% and 0.4% more likely to cover additional distances in power zones 0–5 and 10–15 SSGs/kg, respectively (ORs 1.005 and 1.004). Player load changes from low to high or moderate to high did not significantly affect group performance ($p > 0.05$).

Discussion

The present study aimed to investigate the effects of a 4-week small-sided games (SSGs) intervention combined with running-based high-intensity interval training (HIIT) on the physical fitness of collegiate male soccer players. The main findings showed that the SSGs intervention combined with HIIT had a positive impact on the physical fitness of collegiate male soccer players. However, the improvements observed across various fitness variables were generally small, and in some cases, such as the

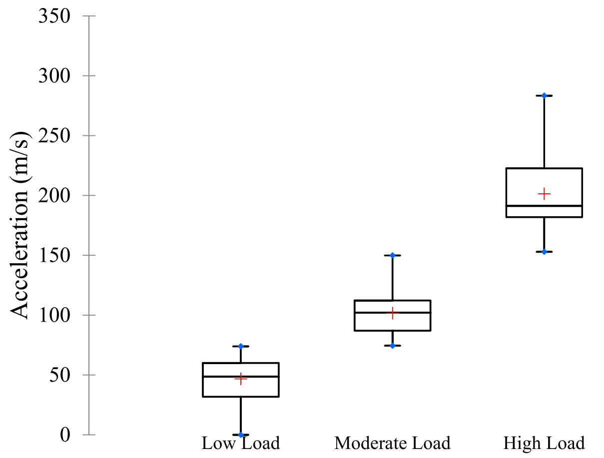

FIGURE 4
Classification of player load.

countermovement jump (CMJ), performance slightly decreased in both groups. These modest improvements, while not reaching statistical significance, were associated with small to moderate effect sizes, indicating that the combined training approach could still be potentially beneficial for enhancing athletic performance among collegiate male soccer players, albeit with some limitations.

Firstly, the intervention group, that underwent the combined SSGs and HIIT training, showed noteworthy improvements in overall physical fitness measures compared to the control group. Specifically, improvements were observed in the asymmetry index, mean RSA, worst RSA, CMJ, and the 30–15IFT, with small to moderate effect sizes. Despite the decrease in CMJ performance, the observed improvements in other areas, particularly in RSA and 30–15IFT, suggest that the combined SSGs and HIIT training might still have positively impacted aspects of physical fitness relevant to soccer performance. The combination of SSGs and HIIT interventions may have contributed to these improvements in physical fitness (Arslan et al., 2021). Small-sided games are known to stimulate acute responses above 85% of maximal heart rate and offer an effective method for enhancing cardiovascular fitness and specific neuromuscular aspects crucial for endurance performance (Los Arcos et al., 2015). The intermittent nature of high-intensity efforts in SSGs promotes enhanced elastic energy storage and release during subsequent jumps, leading to improved CMJ performance (Clemente et al., 2021b). However, the observed decrease in CMJ might be explained by factors such as accumulated fatigue over the intervention period or the focus of the training on endurance and agility rather than explosive power (Gathercole et al., 2015). High-intensity interval training has also been shown to elicit favorable adaptations in endurance performance, with increased mitochondrial content and oxygen consumption in muscle tissue leading to improved aerobic responses (Atakan et al., 2021). The combination of both SSGs and HIIT interventions in the present study likely synergized these effects, contributing to the observed improvements in RSA, and 30–15IFT (Rabbani et al., 2019).

The experimental group showed higher likelihoods of increased heart rate load per minute, reduced time in speed zone 2, elevated impact zones, greater maximum deceleration, decreased time in acceleration zones, and greater distances covered in power zones compared to the control group. This is a typical example of the dose-

TABLE 3 Logistic regression model parameters for determining the predictive variables.

Variables	*B*	Se	Z	*p*	Odds ratio	95% CI	
						Lower	Upper
Intercept	−0.091	1.003	−0.091	0.928	0.913	0.128	6.522
Hr Load	0.004	0.007	0.651	0.515	1.004	0.991	1.018
Hr Load Per Min	0.471	0.188	2.504	0.012*	1.602	1.108	2.316
Time in Speed Zone 2 (secs)	−0.004	0.001	−2.474	0.013*	0.996	0.994	0.999
Impact Zones: 3–5 G (Impacts)	−0.013	0.002	−5.363	0.001*	0.987	0.983	0.992
Max Deceleration (m/s/s)	−0.107	0.052	−2.072	0.038*	0.898	0.812	0.994
Power Score (SSGs/kg)	0.019	0.071	0.269	0.788	1.019	0.887	1.172
Distance in Speed Zone 2 (metres)	0.001	0.001	1.318	0.188	1.001	0.999	1.003
Time in Acceleration Zones: 1–2 m/s/s (secs)	−0.050	0.006	−8.218	0.001*	0.951	0.940	0.963
Distance in Power Zone: 0–5 SSGs/kg (metres)	0.005	0.001	7.121	0.001*	1.005	1.004	1.007
Distance in Power Zone: 10–15 SSGs/kg (metres)	0.004	0.001	3.181	0.001*	1.004	1.001	1.006
Player Load							
Low Load – High Load	0.056	0.884	0.064	0.949	1.058	0.187	5.986
Moderate Load – High Load	0.261	0.721	0.362	0.717	1.298	0.316	5.334

Note. *Sig; Nagelkerke R^2 = 0.262; Hosmer Lemeshow (p = 0.810); Classification Accuracy = 0.682; AUC, 0.759.

response relationship, referring to the relationship between the dose of the intervention and its effect on different outcomes (Impellizzeri et al., 2023). For instance, a previous study explored the links between accumulated external load and changes in body composition, isokinetic strength, and aerobic capacity in professional soccer players over a 10-week period (Clemente et al., 2019). The authors found significant positive correlations between sprinting distance and percentage differences in body mass, heart rate maximum (HRmax), and specific strength ratios. These results underpin the importance of monitoring external load to enhance players' physical performance and mitigate injury risks in soccer, indicating dose-response relationships using external load variables.

The analysis of external load measures revealed notable differences between the intervention and control groups. The experimental group exhibited higher heart rate load per minute and increased distances covered in power zones (0–5 SSGs/kg and 10–15 SSGs/kg), alongside elevated impact zones and maximum deceleration, compared to the control group. Specifically, the odds ratios for heart rate load per minute (OR 1.602) and distances in power zones (OR 1.005 and 1.004) indicated a greater likelihood of increased load and performance in the experimental group. These findings underscore the impact of the combined SSGs and HIIT approach on enhancing external load variables, which are critical for assessing training intensity and player performance (Rabbani et al., 2019). However, shifts in load categories from low to high or moderate to high did not significantly influence changes in physical fitness measures, suggesting that while external load is an important factor, its direct relationship with performance improvements over a short intervention period may be complex and warrant further investigation.

Notwithstanding the findings of our study, further research with larger sample size and potentially longer intervention periods may be warranted to strengthen the evidence and draw more robust conclusions. Additionally, future studies may consider examining the effects of the intervention on other performance-related outcomes and exploring potential differences based on individual player characteristics, such as skill levels and training experience. Still, the present study contributes to the understanding of the effectiveness of the combined SSGs and HIIT training intervention in collegiate male soccer players. The findings demonstrate the potential of this approach to enhance physical fitness, which has implications for optimizing training strategies and improving athletic performance in the sport of soccer.

Conclusion

In conclusion, the 4-week intervention combining SSGs with running-based HIIT did not produce statistically significant improvements in most physical fitness variables when compared to the control group. Although the experimental group showed positive trends with small to moderate effect sizes in variables such as the RSA and the 30–15IFT, these changes did not reach statistical significance. The modest improvements observed in the experimental group suggest that while the combined SSGs and HIIT approach has potential, its current implementation may not yield substantial changes in physical fitness over a 4-week period. Notably, some variables, such as the CMJ, even exhibited decreases, indicating that the intervention's impact may be limited or inconsistent.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the ethics committee of the University of Taipei (UT-IRB-2020-061). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

YQ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing–original draft, Writing–review and editing. YZ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Writing–original draft, Writing–review and editing. RaM: Formal Analysis, Writing–original draft, Writing–review and editing. RyM: Writing–original draft, Writing–review and editing. RS: Writing–original draft, Writing–review and editing. C-HH: Methodology, Writing–original draft, Writing–review and editing. Y-SC: Conceptualization, Methodology, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fphys.2024.1466386/full#supplementary-material

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Optimal dose of vigorous physical activity on cardiorespiratory and perceptual response for sedentary youths using internal load monitoring

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Introduction: Vigorous physical activity (VPA) has been demonstrated to enhance cardiorespiratory fitness (CRF) in sedentary college students more effectively than other PA. However, differences in training volume may affect this outcome. This study examines the physiological, psychological, and internal training load (ITL) characteristics of VPA with varying volumes in a single session.

Methods: Thirty sedentary college students were divided into three groups: high-intensity interval training (HIIT), sprint interval training (SIT), and threshold training (THR). PA process was monitored. The study measured various cardiorespiratory parameters, including heart rate (HR), respiratory waveform and amplitude, respiratory rate (RR), tidal volume (TV), minute ventilation volume (VE), fractional concentration of oxygen in end-tidal gas (O2%), fractional concentration of end-tidal carbon dioxide (CO2%), global oxygen consumption (VO2), carbon dioxide discharge (VCO2), and the amount of carbon dioxide in the air. The following physiological indicators were measured: carbon dioxide discharge (VCO2), Oxygen pulse (OP), and respiratory exchange ratio (RER). Additionally, subjective perception indicators were recorded, including the feeling scale (FS), rating of perceived exertion (RPE), and dual-mode model (DMM). The session-RPE (s-RPE) and Edward's TRIMP were used to measure ITL.

Results: There were no significant differences in HR across the three conditions. THR had the highest level of TV ($p = 0.043$), but RR was significantly lower than that of HIIT and SIT ($p < 0.01$). HIIT had the highest levels of VO2, VCO2, O2%, and OP ($p < 0.05$). RPE was higher in HIIT and SIT compared to THR ($p < 0.01$), but the difference in FS was not significant. The DMM time-domain trajectories were similar in HIIT and THR. The correlation between exercise intensity, RPE, and FS was highest in THR group ($r = 0.453$, $r = -0.58$, $r = -0.885$). ITL did not show a significant difference between three conditions, but TRIMP and s-RPE readings were opposite in magnitude.

Conclusion: This study proposes that using an appropriate amount of THR to foster interest and adaptive strength during the PA habit establishment period, incorporating HIIT to enhance exercise efficiency during the adaptation period, and implementing SIT to reduce the monotony may effectively enhance the cardiorespiratory fitness of sedentary college students and establish PA habit.

KEYWORDS

physical activity, sedentary behavior, cardiorespiratory fitness, psychological responses, training load

Introduction

Sedentary behavior (SB) has become a common daily habit worldwide due to the development of modern society. SB is defined as any waking behavior that involves energy expenditure of ≤1.5 METs while sitting or reclining (World Health Organization, 2020). According to the World Health Organization's (WHO) Global Status Report on Physical Activity 2022, 28% of the world's population engages in SB. This behavior has become prevalent among college students, particularly on university campuses, due to academic pressures. SB is a common habit among college students (World Health Organization, 2022). Numerous studies have shown that SB not only reduces interest in exercise but also causes physical symptoms such as poor circulation, disruption of endocrine balance, and musculoskeletal abnormalities. These symptoms can lead to various diseases, including cardiovascular and metabolic syndromes (Curran et al., 2023; Pinto et al., 2023). The American Heart Association (AHA) has demonstrated that reduced cardiorespiratory fitness (CRF) is the primary risk factor for SB. This negatively impacts the physical functioning and quality of life of college students (Lavie et al., 2019).

In response to the above, the WHO guidelines on physical activity and sedentary behavior indicate that regular physical activity (PA), as a non-pharmacological tool, can effectively increase stroke volume, maximal oxygen consumption, and oxygen pulsation, thereby improving oxygen uptake, vascular wall elasticity, and cardiac output, and promoting the development of CRF (World Health Organization, 2020). PA, as a non-pharmacological tool, can effectively increase stroke volume, maximal oxygen consumption, and oxygen pulsation, thereby improving oxygen uptake, vascular wall elasticity, and cardiac output, and promoting the development of CRF. However, as the scientific level of exercise increases, a large number of studies have found that the effects of different types of exercise on CRF vary. Among these, vigorous physical activity (VPA) has been shown to provide individuals with greater cardiorespiratory stimulation in a single session, making its long-term benefits superior to those of other exercises. For instance, Rachelle discovered that VPA not only improved cardiorespiratory fitness more effectively than moderate-intensity continuous training (MICT), but also saved time during exercise (Sultana et al., 2019). In a year-long study, Taylor discovered that individuals who participated in VPA experienced greater improvements in VO2max and exercise tolerance compared to those who engaged in MICT (Taylor et al., 2020). Similarly, Wisløff found that VPA had a more significant effect on brachial artery flow and mitochondrial function, leading to a higher level of CRF improvement from a mechanistic perspective (Wisløff et al., 2007). Therefore, due to the characteristics of 'high benefit and short time', various VPA programs have gained attention in the field of sports training and clinical research.

While the beneficial impact of VPA on CRF has been extensively proven, the advancement of technology and quantification of training loads has led to numerous studies monitoring the subjective and physiological loads of individuals during exercise through internal training load (ITL) (McLaren et al., 2018). This makes it more challenging to enhance the resolution and precision of our training. It has been discovered that different training modes, even at similar intensities, can still result in differences in physiological and psychological parameters among individuals (Ekkekakis et al., 2002; Mooren et al., 2023). Therefore, setting the training volume is a crucial factor in developing training programs and prescribing exercises. VPA can be divided into three types of training based on differences in training capacity: high-intensity interval training (HIIT), sprint interval training (SIT), and threshold training (THR). Research indicates that each of the three types of exercise has distinct physiological and psychological effects on individuals. Michael's study found that the HIIT group had a 4% higher time-trial performance than the SIT group, and that maximal aerobic power and velocity were significantly improved in the HIIT group (Rosenblat et al., 2020). Alejandro demonstrated that SIT improved individuals' strength more than HIIT did (Pérez-Castilla et al., 2023), while Tsung found that HIIT and THR had similar effects on CRF in sedentary college students (Chiang et al., 2023). Up to now, while the variations in athletic performance enhancement, strength quality improvement, and physical health interventions among the three groups have been preliminarily confirmed, there is still a lack of monitoring reports and characterization of CRF parameters, subjective perception, and ITL during exercise.

To better quantify the dosage characteristics and physiological mechanisms of cardiorespiratory responses, exercise perception, and subjective/physiological loads of sedentary college students due to differences in training capacity in VPA, this study was conducted to monitor the process of three exercise conditions. This study aims to determine the optimal dose of VPA for improving CRF, explain the physiological mechanisms behind it, and provide a scientific exercise prescription and theoretical basis for promoting cardiopulmonary health, cultivating interest in exercise, and enhancing exercise efficiency in sedentary college students. Based on the rationale provided above, this study's hypotheses are: (I) The expression levels of HR may be similar in all three conditions; (II) THR exhibits the highest oxygen uptake while SIT exhibits the lowest; (III) Subjective fatigue levels are THR > HIIT > SIT, while the opposite is true for the perception of movement; (IV) THR exhibits the highest subjective and physiological loads, whereas HIIT and SIT do not differ significantly; and (V) The subjective and physiological loads are the highest in THR, whereas HIIT and SIT do not differ significantly.

Materials and methods

This study was a randomized controlled trial conducted at the Exercise Human Science Laboratory of Beijing Normal University. As this study is an exercise physiology monitoring experiment, the purpose is to assess the expression characteristics of physiological and psychological indexes of sedentary adolescents during different modes of VPA, and the outcome indexes are all continuous variables and have no absolute categorical variables, so there is no blank control group. The aim was to identify the most effective VPA program for improving CRF and perceptions of exercise experience in sedentary adolescents. During the experiment, participants were randomized into HIIT, SIT, and THR groups. The experimental environment was set up in a relatively constant temperature laboratory (23°C–26°C) with supervised power cycling exercises. The experimental period was from February 2023 to April 2023. Tests are standardized between 13:00 and 17:00. In order to familiarize the participants with the exercise protocol and the equipment, and to reduce the probability of risky events during the experiment, all personnel were asked to perform at least 1 pre-experiment and exercise practice. Prior to the experiment, participants were asked to maintain a normal routine and refrain from strenuous exercise for 24 h prior to the exercise session, and to refrain from consuming large amounts of food and water for 2 h prior to the experiment to ensure optimal hydration.

Participants

The present study was based on the WHO guidelines on physical activity and sedentary behavior for sedentary populations (World Health Organization, 2020), and was conducted according to the Bassett protocol using the International Physical Activity Questionnaire (IPAQ). The International Physical Activity Questionnaire (IPAQ) initially recruited 35 participants who self-reported more than 8 h of sedentary time per day and less than 30min of moderate to vigorous physical activity (Bassett, 2003). All participants were screened to ensure that they had no prior long-term occupational training or exercise habits. Twenty-seven male and eight female adolescents between the ages of 20 and 25 were included. However, due to the large difference in numbers between genders and the age range of the eight females, the numbers did not fit a normal distribution. Therefore, in this study, in order to reduce systematic error and heterogeneity to improve the reliability of the results, only 27 male adolescents whose age fit the normal distribution were included in the final experiment.

The allocation of subjects to the different exercise groups was performed in a blinded manner using a randomized lottery. Prior to the start of the experiment, all subjects were asked to sign an informed consent form, which included an acknowledgement of the experimental risks, no history of psychiatric disorders, cardiovascular disease, muscle contraindications, or adverse drug experiences. At the same time, participants were informed that they would be required to undergo at least two or more exercise interventions, including the pre-experiment and the formal experiment. In addition, all experimenters were blinded to ensure the privacy of the participants. The experiment was approved by the

TABLE 1 Participants' physical characteristics.

	HIIT	SIT	THR
Numbers (n)	11	7	9
Age (yr)	22.82 ± 1.47	23.57 ± 1.62	23 ± 1
Body mass (kg)	77 ± 7.39	76.14 ± 5.93	76 ± 5.92
Height (m)	1.77 ± 0.05	1.77 ± 0.04	1.78 ± 0.05
BMI (kg/m2)	24.43 ± 1.42	24.41 ± 1.42	23.86 ± 1.46
HRrest (bpm)	76.27 ± 4.69	77.29 ± 5.94	77.33 ± 5.45
HRmax (bpm)	191.18 ± 1.47	190.43 ± 1.62	189.56 ± 1.13
Sedentary behavior (hour/day)	8.63 ± 1.28	8.71 ± 1.12	8.25 ± 0.86
MVPA (min/day)	26.18 ± 6.19	27.42 ± 6.24	26.77 ± 5.85

Human Experimentation Ethics Committee of the School of Physical Education and Sport, Beijing Normal University (approval number: TY20220629, see Supplement one for details). The experiment was conducted in strict accordance with the requirements and procedures of the Institutional Review Board, and the demographic information is shown in Table 1.

Procedures

The exercise interventions consisted of power cycling. The subjects' RPE, FS, and FAS scores were recorded every minute until completion. During the implementation, supervisors strictly followed the target HR intervals specified by the AHA to control exercise intensity. Failure to achieve the target intensity will result in an invalid experimental procedure.

Baseline testing

Before the experiment, the subjects' height and weight were measured to calculate their BMI (kg/m2). The maximum exercise capacity of each individual was determined through graded exercise tests (GXT) performed on a cycle ergometer (Chengdu Taimeng Technology Co., Ltd.). The participants were warmed up with a resistance of 50 W for 2 min, followed by an increase of 20 W every minute until complete exhaustion (cycle speed below 50 rpm). Verbal encouragement was provided by the experimenter to ensure the integrity of the experiment. VO2 and HR were recorded during exercise using the same brand of human physiological metabolic analyzer and POLAR Verity Sense, with a sampling frequency of one time/s. The highest values of VO2max and HRmax were recorded within 15–30 s after the end of the test, provided that the individual's RERmax was greater than 1.10 or real-time HR was less than or equal to 220 minus the individual's age (Olney et al., 2018). These values were then used to determine the intensity of subsequent exercise sessions.

High-intensity interval training

The HIIT group used Wisløff's classic protocol with modifications (Wisløff et al., 2007). The whole program lasted about 20 min Including a 5 min warm-up, during which the heart rate was kept above 50% HRmax. This was followed by five sets of interval training. Each set consisted of a 2min high-intensity sprint at 85% HRmax or higher. Bridging to 3min of active recovery exercise, participants reduced the intensity of the active recovery activity on their own but did not stop exercising.

Sprint interval training

The SIT group used Kimberly's protocol exclusively (Wood et al., 2016). The duration of the entire program was approximately 20 min Which included a 5 min warm-up during which the heart rate was maintained above 50% HRmax. Unlike HIIT, the SIT group reduced the duration of sprinting and recovery and bridged 10 sets of interval training. Each set consisted of a 30-s high-intensity sprint at an intensity above 85% HRmax. This was interspersed with 1.5 min of active recovery exercise, where participants reduced the intensity on their own for active relaxation activities but did not stop exercising.

Threshold training

In the THR group, the exercise mode was traditional high-intensity target heart rate training, so the Chiang classic program was used (Chiang et al., 2023). The duration of the whole process was 20 min Compared to HIIT and SIT, the whole process of THR did not have any recovery phase. First, participants performed a 5-min warm-up to elevate HR to within the target intensity range of 70%–80% HRmax (≈95% VT1). Afterwards, continuous exercise without intervals was performed until the end of training.

Measurements

Heart rate monitoring

The POLAR Verity Sense was used as HR testing instrument in this study. It was worn on the left arm throughout the exercise and had a sampling frequency of one time/s. During the wearing process, the biosensing contact surface of the POLAR watch was uniformly cleaned and maintained to avoid any interference with HR data collection. The watch was worn on the top of the left side of the arm in a strictly regulated position to prevent any special reasons, such as body fluid obstruction, from affecting the results. To ensure data quality, the experimental staff will conduct a 3–5 min data collection test before the official experiment using the POLAR PC software. This will allow them to check the real-time HR collection status and make any necessary adjustments to the equipment and experiment steps based on technical issues that may arise on site.

Respiratory metabolism measurement

The HPS-10 human metabolism monitor (Chengdu Taimeng Technology Co., Ltd.) was used to monitor the respiratory index during the exercise. The subjects wore wireless respiratory and metabolic waveform monitoring masks throughout the exercise process. The normal body movements of the subjects were not affected during the exercise. The respiratory parameters included in this study were respiratory waveform and amplitude, respiratory rate (RR), tidal volume (TV), minute ventilation volume (VE), fractional concentration of oxygen in end-tidal gas (O2), the volume of oxygen in end-tidal gas (O2), fractional concentration of end-tidal carbon dioxide (CO2), global oxygen consumption (VO2), carbon dioxide discharge (VCO2), oxygen pulse (OP), and respiratory exchange ratio (RER). The experimenter manually recorded the cardiopulmonary parameters every minute and entered them into the experiment log.

Perceptual response assessment

Hardy & Rejeski's feeling scale (FS) (Hardy and Rejeski, 1989) and Borg's rating of perceived exertion scale-10 items (RPE) (Li et al., 2023) were used to evaluate subjective perception and provide an overall assessment of subjects' subjective motor sensations during a single training session. Additionally, a circular model-based dual-mode model (DMM) was employed to illustrate the dose-response relationship between RPE and FS in two orthogonal/bipolar dimensions (Ekkekakis et al., 2002). In the case of the RPE and FS included in this study, the four quadrants of the DMM represent four psychological states: the vitality-pleasure quadrant (quadrant 4), the fatigue-pleasure quadrant (quadrant 1), the vitality-dullness quadrant (quadrant 3), and the fatigue-dullness quadrant (quadrant 4). Outside of these quadrants, there are no significant mental fluctuations. By observing the time-domain trajectory of the DMM, experimenters can clearly understand the changes in the two-factor dynamic relationship between exerciser experience to fatigue during the exercise process, and provide data clues for increasing interest in exercise and adjusting the exercise prescription. During the experiment, athletes reported their scores at 1-min intervals and at the peak of each motor state. The experimenter recorded the scores. After the experiment, the data were organized, analyzed, and used to establish DMM and calculate ITL.

Internal training load evaluation

In this study, the subjective and physiological loads of each group of subjects were calculated by training impulse. In this case, training impulse used Foster's session RPE (s-RPE) (2001) (Foster, 1998) based on subjective fatigue level with Edwards' five-zone Edwards' TRIMP (SHRZ) (1993) (Castagna et al., 2011) based on HR characteristics. Unlike the traditional Banister's TRIMP (1991) (Mekjavic et al., 1991), the SHRZ divides the HR intervals and thus not only calculates an individual's load per unit time in a more refined manner, but also reflects the load distribution characteristics during exercise.

①The formula for session-RPE is as follows:

$$session - RPE = T \times RPE$$

②The formula for Edward's TRIMP is as follows:

$$TRIMP = (T \times 1) + (T \times 2) + (T \times 3) + (T \times 4) + (T \times 5)$$

HR zones (%HRmax)	Coefficient
90%–100%	5
80%–90%	4
70%–80%	3
60%–70%	2
50%–60%	1

T represents the duration of the exercise. TRIMP, values are calculated by multiplying the duration within each interval by the corresponding weighting factor. The sum of the TRIMP, values for each interval is the total TRIMP, value for the training period. The RPE, is calculated using Borg's CR-10 RPE.

Statistical analysis

All data were counted and analyzed using IBM SPSS Statistics_26 and descriptive statistics and reliability tests were performed after normality tests. All individual results were then combined and presented as mean ± standard deviation. First, the overall mean differences of all outcome variables were compared and calibrated by one-way analysis of variance (ANOVA). The mean values of HR, TV, RR, and VE represent the total cardiorespiratory load imposed by the three VPAs per unit of time, while the mean values of O2%, CO2%, VO2, VCO2, RER, and VCO2/HR reflect the respiratory metabolism and oxygen uptake of an individual during a single bout of exercise and are used to evaluate the effects of acute VPAs on CRF in a single session. RPE and FS reflect the effects of different exercise regimens on an individual's subjective mood and experience, while TRIMP and s-RPE represent the level of perceptual and physiological load experienced by an individual during exercise and are used to evaluate the effects of a single training session. Second, repeated-measures one-way ANOVA and multivariate analysis of variance (MANOVA) were used to compare and analyze the expression levels of each index at different time points to explore the time-domain changes of individual cardiorespiratory response, perceptual load, and physiological load during different VPA and to provide a reference basis for improving the training program. HR, FS, and RPE were analyzed by Pearson's coefficients to investigate the effects of training volume on subjective mood of exercisers at similar exercise intensities (HRmax). Subjective mood of exercisers at similar exercise intensities (HRmax). The analysis of effect sizes was assessed with the Greenhouse-Geisser Assumed Sphericity test, and the results of cases that did not meet the hypotheses were corrected using the Greenhouse-Geisser method. Post hoc tests for each outcome were performed using the Bonferroni test, with a significance threshold of $p < 0.05$.

Results

There were no risk events in this study. Compliance was 100% in the HIIT group, three withdrew during the SIT for 70% compliance, and one was unable to complete the test during the THR and voluntarily requested to be transferred to the HIIT group for training for 90% compliance. The results of the cardiorespiratory fitness test indicated that HR and ventilatory efficiency were similar across all three exercise conditions. However, there were notable differences in gas exchange rates, particularly in VO2, VCO2, and OP, which increased with the training volume but did not exceed the expected levels when the exercise type remained constant. The results of the study showed that intermittent exercise elicited higher levels of fatigue compared to continuous exercise. However, the participants' perceptions of exercise were generally low and did not significantly differ among the three groups. The training load results indicate that although the subjective and physiological loads of the three conditions were not significantly different, the magnitude of the readings was opposite to each other, and the load distribution characteristics were closely related to the training volume.

Heart rate characteristics during different training

The results showed that the HR time domain and amplitude characteristics of the three exercise conditions differed significantly (Figure 1A). Among them, SIT had the smallest amplitude and shortest peak period, HIIT had moderate amplitude and larger period than SIT, and THR was relatively stable without large fluctuations. ANOVA *post hoc* analyses showed that (Figure 1B), even though the HRpeak of THR was lower than that of HIIT and SIT, there was no statistically significant difference among the three conditions ($p > 0.05$). MANOVA repeated measures showed (Figure 1C) that the HRs of the three conditions were not all equal (HIIT: F = 28.915; SIT: F = 10.965; THR: F = 28.509). In the HIIT group, HR increased significantly in sessions 1–2 ($p < 0.01$), was more moderate in sessions 2–4 ($p > 0.08$), but climbed again in sessions 4–5 ($p = 0.01$), and then did not fluctuate significantly ($p = 0.165$); in the SIT group, HR increased significantly in the pre-exercise period (sessions 1–3) ($p < 0.02$), and did not change significantly in the late period (sessions 4–6) ($p > 0.05$); the THR group only increased in the early period (sessions 1–2), and did not change significantly in the late period (sessions 4–6) ($p > 0.05$); and in the THR group, it was only in the early period (sessions 1–2), and did not change significantly. ($p < 0.02$) in the SIT group in the pre-exercise period (session 1–3), but no significant change in the later period (session 4–6) ($p > 0.05$); HR in the THR group climbed only briefly in the early period of exercise (session 1–2) ($p < 0.01$), and then stabilized thereafter ($p > 0.1$). The HR interval characteristics show (Figure 1D) that the HRs of the three conditions are mainly distributed in the range of 140–170 bpm. Although the intensity of the three conditions is similar, the HR interval characteristics are different. Among them, 150-160bpm accounted for the case of HIIT < SIT < THR, while 140-150bpm and 160-170bpm accounted for the opposite of the former. All the details are shown in Table 2.

Respiratory metabolism characteristics during different training

Respiratory metabolic characteristics showed (Figure 2A) that the amplitude of respiratory waveforms in the three exercise conditions was similar to that of HR, characterized as: THR was the most stable; SIT had a small amplitude and a short period; and HIIT had a large amplitude and a long period. The results of the *post hoc* analysis of the ANOVA showed that, although the TVmean of the three conditions, VEmean/peak were not statistically significant, but the TVmean of THR group was higher than that of HIIT group ($p = 0.043$) (Figures 2B–D), and the difference of RR was significant ($p < 0.01$), which was as follows: SIT > HIIT>THR (Figure 2C). Gas exchange status showed (Figures 3A, B, I, J) that the mean and peak expression levels of VO2, VCO2 and O2% were significantly higher in HIIT than in the other two exercises (VO2mean: HIIT-SIT: $p = 0.010$, HIIT-THR: $p = 0.018$; VO2peak: HIIT-SIT: $p = 0.038$, HIIT-THR: $p = 0.018$; VO2peak: HIIT-SIT: $p = 0.038$, HIIT-THR: $p = 0.018$). 0.038, HIIT-THR: $p = 0.020$; VCO2mean: HIIT-SIT: $p = 0.002$, HIIT-THR: $p = 0.012$; VCO2peak: HIIT-SIT: $p = 0.001$, HIIT-

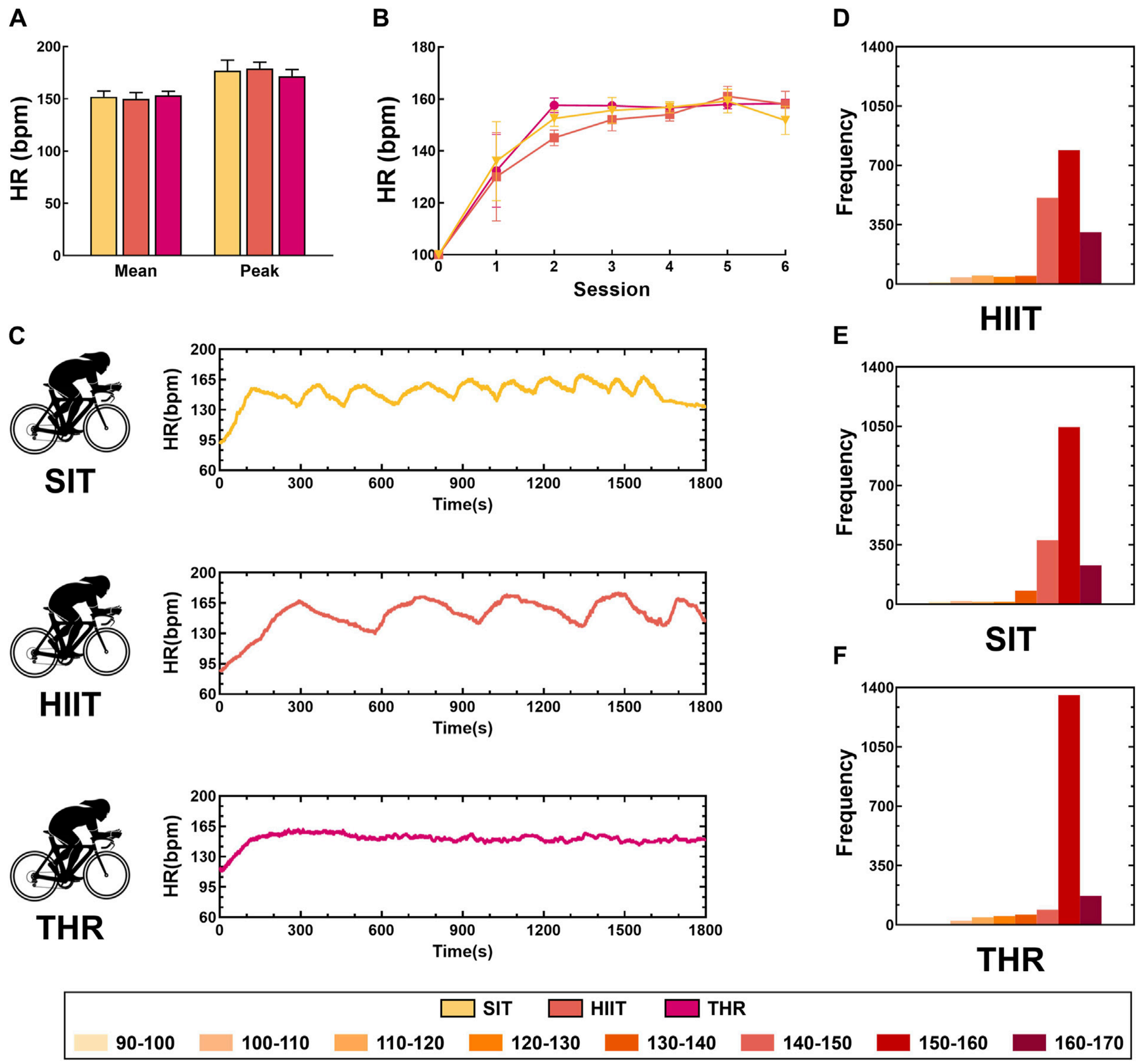

FIGURE 1
Characteristics of heart rate distribution intervals and time domain changes in different states. Note: **(A)** Expression of HRmean and HRpeak in different states; **(B)** Time-domain characteristics of HR divided by session; **(C)** Time-domain characteristics of HR in different states; **(D)** HR intervals in HIIT; **(E)** HR intervals in SIT; **(F)** HR intervals in THR.

THR: $p = 0.023$; O2%: HIIT-SIT: $p = 0.027$, HIIT-THR: $p = 0.001$), but SIT and THR were not statistically significant.

MANOVA repeated measurements (Figures 3C, D, I, J) showed that VO2, VCO2, and CO2% increased consistently across all conditions, except for VCO2, which did not increase significantly at the end of the HIIT and SIT training sessions (sessions 5–6), while O2% decreased (VO2: HIIT: F = 72.401; SIT: F = 95.713; THR: F = 46.682, $p < 0\ 05$; VCO2: HIIT: F = 94.457, SIT: F = 94.457, THR: F = 46.682, $p < 0\ 05$). 72.401; SIT: F = 95.713; THR: F = 46.682, $p < 0.05$; VCO2: HIIT: F = 94.457, SIT: F = 73.434, THR: F = 41.470, $p < 0.05$; O2%: HIIT: F = 213.728, SIT: F = 96.630, THR: F = 157.413, $p \leq 0.01$; CO2%: HIIT: F = 221.969, SIT: F = 97.721, THR: F = 117.618, $p \leq 0.01$). The rest of the results showed that the RER was similar for THREE conditions (Figures 3E), with no significant fluctuations across the motions in the remaining phases (Figures 3G), except for a significant increase in THR at the end of the session (session 5–6) (F = 1.440, $p = 0.011$). Notably, OP in HIIT was significantly higher than THR ($p = 0.011$) (Figures 3F). In particular, HIIT increased significantly (F = 17.082, $p < 0.05$) in the pre-exercise period (session 1–3) and exceeded THR ($p = 0.013$) at session 2, while SIT and THR continued to increase (SIT: F = 44.490, $p < 0.05$; THR: F = 28.165, $p < 0.05$) (Figures 3H). The details of the time-domain variations of VO2 and VCO2 are shown in Figure 4. All the details are shown in Table 3.

Characterization of motion perception and training load

The subjective perception results showed that individuals' RPE in THR was significantly lower than HIIT ($p < 0.01$) and SIT ($p =$

TABLE 2 Expression status of heart rate in different states/stages and distribution intervals.

HIIT								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
HR (bpm)	149.93 ± 6.44	178.55 ± 5.73	129.77 ± 13.16	145.16 ± 9.36	152.29 ± 10.85	154.13 ± 6.66	160.55 ± 6.07	157.75 ± 5.16
	HR-Range							
	90–100	100–110	110–120	120–130	130–140	140–150	150–160	160–170
Frequency (s)	11	40	50	43	49	509	790	306
Proportion (%)	0.61	2.22	2.78	2.39	2.73	28.31	43.94	17.02
SIT								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
HR (bpm)	151.95 ± 5.4	176.86 ± 10.12	136.04 ± 10.54	152.46 ± 5.64	155.57 ± 7.75	156.74 ± 2.46	159.17 ± 6.16	151.72 ± 12.11
	HR-Range							
	90–100	100–110	110–120	120–130	130–140	140–150	150–160	160–170
Frequency (s)	15	20	15	15	81	377	1045	230
Proportion (%)	0.83	1.11	0.83	0.83	4.51	20.97	58.12	12.79
THR								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
HR (bpm)	153.32 ± 3.73	171.56 ± 6.46	132.34 ± 10.11	157.56 ± 2.68	157.39 ± 5.11	156.57 ± 4.65	157.93 ± 5.57	158.17 ± 7.93
	HR-Range							
	90–100	100–110	110–120	120–130	130–140	140–150	150–160	160–170
Frequency (s)	0	25	45	52	60	90	1355	171
Proportion (%)	0	1.39	2.5	2.89	3.34	5.01	75.36	9.51

0.001), while FS in three conditions was not significantly different (Figures 5A, C). MANOVA repeated measures showed (Figures 5B, D) that RPE in all three conditions showed a continuous increase (HIIT: F = 471.656, SIT: F = 166.956, SIT: F = 166.956, SIT: F = 166.956, SIT: F = 166.956) and a substantial decrease at the end of the exercise (session 5–6). Conditions showed a continuous increase in RPE and a significant decrease at the end of exercise (session 5–6) (HIIT: F = 471.656, SIT: F = 166.953, THR: F = 407.549). Both HIIT and SIT flattened in the middle of the exercise (session 2–3) and increased significantly ($p < 0.05$) in the early (session 1–2) and late (session 3–6) periods, while THR continued to increase ($p < 0.01$). FS, on the contrary, showed a continuous decrease and changed from decrease to increase at the end of the exercise (HIIT: F = 283.307, SIT: F = 102.914, THR: F = 305.824). The three trends remained similar, with HIIT and SIT decreasing slowly in the middle of the exercise period (session 2–3), then decreasing sharply in the early (session 1–2) and late (session 3–6) periods ($p < 0.05$), and THR decreasing throughout the exercise period ($p < 0.01$).

The DMM results show (Figures 5F) that the time-domain trajectories of the three conditions are similar, all of them start from the vigorous-pleasant quadrant, move to the fatigue-unpleasant quadrant at the lower right, and gradually approach the vigorous-unpleasant quadrant. Unlike THR, which remained in the vigorous-pleasant quadrant at the second sextile, SIT entered the vigorous-unpleasant quadrant at the end of the phase. Correlation results showed (Figures 5E) that exercise intensity (HR) was positively correlated with subjective fatigue level. Was positively correlated with the correlation rank of THR > SIT > HIIT (r = 0.453, r = 0.449, r = 0.328). Sense of enjoyment, on the other hand, was negatively correlated with both exercise intensity and subjective fatigue level, and the latter correlation was stronger, as shown by the correlation ratings of THR < HIIT < SIT (FS-HR: r = −0.58, r = −0.429, r = −0.42; FS-RPE: r = −0.885, r = −0.84, r = −0.801). This implies that an increase in training volume directly mediates an increase in fatigue levels during high-intensity exercise, and that the onset of fatigue is the primary factor causing a decrease in enjoyment.

The results of the training loads showed that although the differences between the subjective and physiological loads (s-RPE/TRIMP) for the three exercise conditions were not statistically significant, the readings showed the opposite results for s-RPE and TRIMP, with the s-RPE magnitude relationship being: HIIT > SIT>THR, and TRIMP being: HIIT < SIT < THR (Figures 5G, H). SIT < THR (Figures 5G, H). According to Edward's TRIMP, the load distribution of the three conditions is similar: the medium load (Zone 2–3) accounts for more than 80% of the load. The difference is that high load zones (Zones 4–5) and low load zones (Zone 1) are the most prevalent in HIIT, followed by

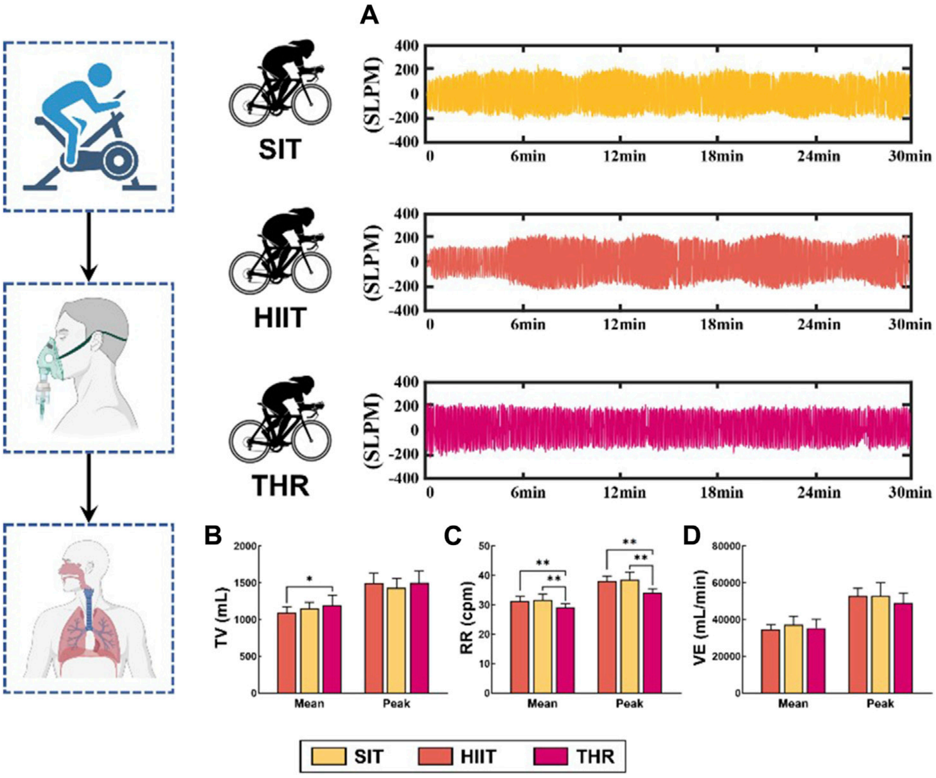

FIGURE 2
Respiratory metabolism in different states. Note: **(A)** Characteristics of respiratory flow rate in different states; **(B–D)**: Expression of respiratory rate/tidal volume/ventilation per minute in different states.

SIT, whereas THR spends most of its time in moderate load zones (Zones 2–3). This phenomenon also suggests that the larger the training volume, the smaller the load interval span, and the smaller the training volume, the greater the load fluctuation (Figures 5I). All the details are shown in Table 4.

Discussion

CRF is a crucial aspect of both physical and mental health. The AHA categorizes it as a 'vital sign' that determines an individual's physiological function, exercise capacity, and quality of life (Ross et al., 2016). Decreased CRF is the primary risk factor for diseases caused by SB that can lead to all-cause-of-death (Lavie et al., 2019). While regular PA has been shown to improve CRF, differences between types of PA remain. Among college students, sedentary behavior is common due to limited exercise time caused by class schedules and academic pressures. To improve the efficiency of physical activity on their cardiorespiratory fitness and overall health, studies have shown the benefits of shortening exercise time and increasing exercise intensity (Winwood et al., 2024). However, this study concludes that simply increasing exercise intensity is not the most effective way to improve exercise efficiency. Therefore, this study compared three different forms of PA to VPA and explored the physiological and psychological significance of training volume in CRF and exercise experience. The study aims to provide more accurate exercise prescriptions and theoretical references for sedentary college students.

The initial discovery of this study is demonstrated through the CRF indicators, such as HR, VO2, and RER. These indicators represent an individual's functional metabolic state and level of stimulation during exercise. Numerous studies have monitored their expression levels to assess the impact of various PAs on the enhancement of physiological and psychological health (Ji et al., 2024). The study results indicate that there were no significant differences in cardio metabolism between the HR and time domain characteristics of the three exercise conditions. All three conditions reached the ACSM recommended optimum cardiovascular training zone or above (Liguori, 2022). However, the THR group exhibited a more stable frequency of HR distribution over 20min compared to the other two groups. Therefore, hypothesis (I) can be accepted. During intermittent exercise (HIIT/SIT), individuals may be in a state with a large span of high and low intensities, making it difficult to effectively control HR within a fixed interval as in continuous exercise. Additionally, three conditions showed differences in respiratory metabolism. For instance, RR and OP were higher in intermittent exercise than in continuous exercise at THR. In the between-group comparison between HIIT and SIT, HIIT exhibited a higher level of respiratory metabolism (VO2/VCO2/O2%) than SIT, which contradicts hypothesis (II) and is consistent with previous findings. Stefano compared the effects of different volumes of intermittent exercise on cardiac vagal reactivity. The results

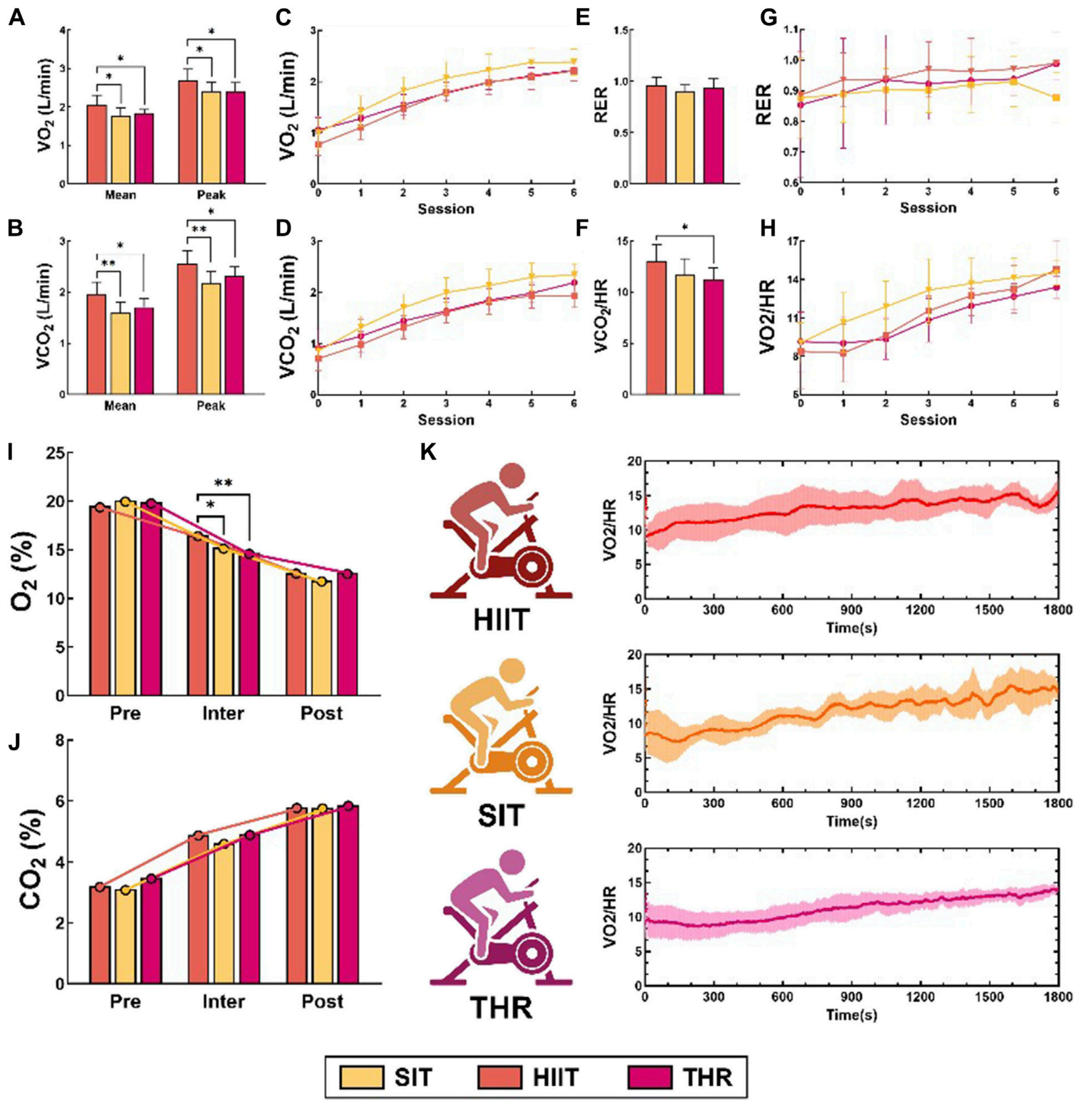

FIGURE 3
Gas exchange in different states. Note: **(A–H)** Mean and peak oxygen uptake in different states; **(B)** Mean and peak carbon dioxide output in different states; **(C)** Time-domain characteristics of oxygen uptake in different states; **(D)** HR intervals in HIIT; **(E)** HR intervals in SIT; **(F)** HR intervals in THR. oxygen uptake in different states; **(D)** Time-domain characteristics of carbon dioxide output in different states; **(E)** Respiratory exchange ratio in different states; **(F)** Oxygen pulse in different states; **(G)** Time-domain characteristics of respiratory exchange ratio; **(H)** Time-domain characteristics of oxygen pulse; **(I)** Expression post-exercise; **(K)** Oxygen pulse in different states.

showed that SIT and HIIT led to higher HRmean, lower HR recovery, and lower HR variability compared to THR. However, the differences between the groups were not statistically significant (Benítez-Flores et al., 2023). Fernando monitored cardiorespiratory responses to constant load exercise and interval exercise. The results showed that the HIIT group had higher levels of VE, VO2mean, and HRmean expression (Beltrami et al., 2021). Focusing on the training capacity aspect of interval exercise, Naves found that VO2peak and HRpeak were generally higher in individuals during HIIT and SIT than THR. However, HIIT had a significant enhancement of the right atrial reservoir and conduit functions, reducing radial and ventricular ejection fraction, and increasing the right ventricular ejection fraction during interval exercise. Additionally, HIIT resulted in a reduction of radial strain and pulmonary vascular

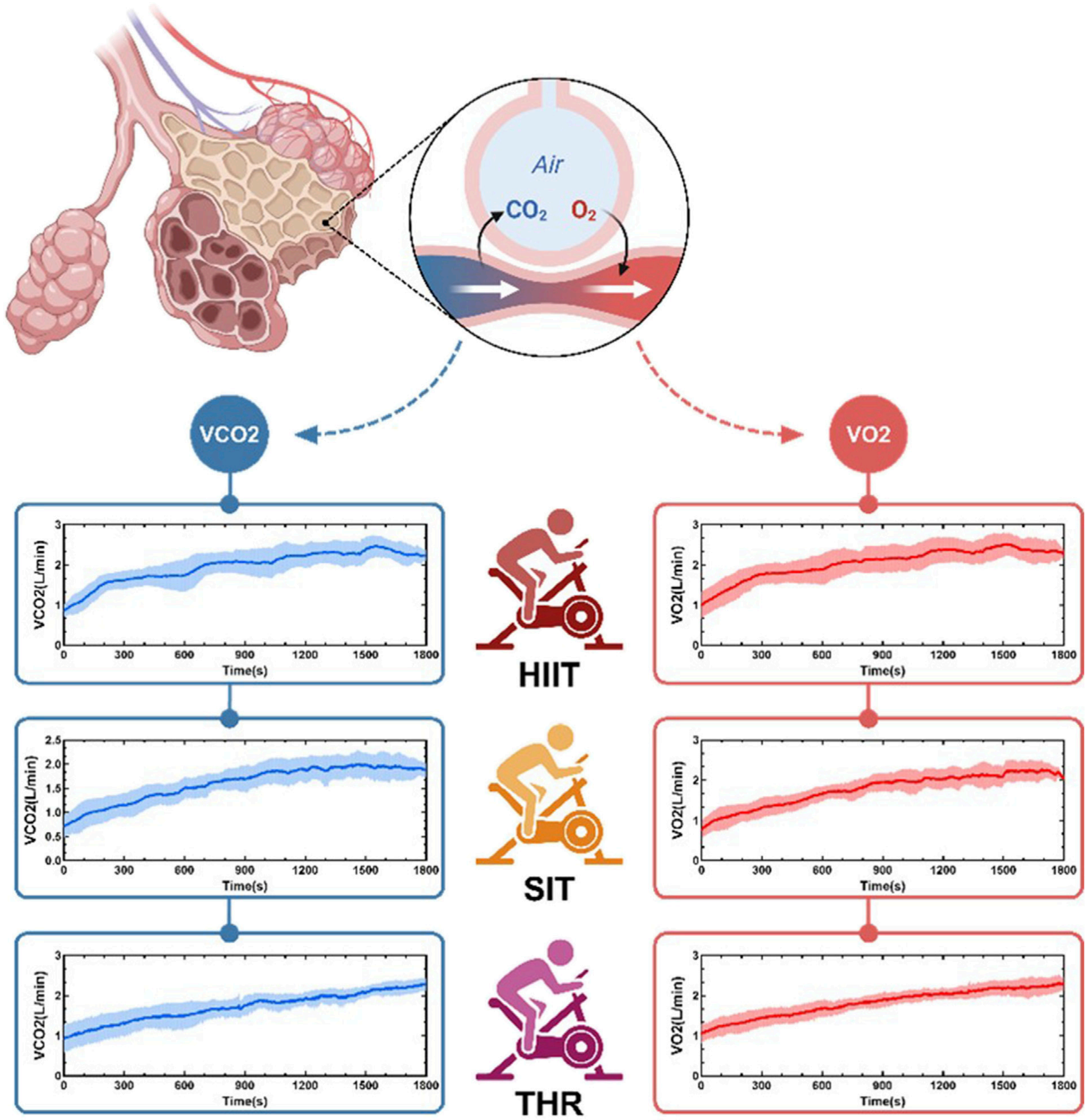

FIGURE 4
Time-domain characteristics of O2 and CO2 in different states of gas exchange.

resistance compared to SIT (Naves et al., 2019). Benjamin's analysis found that in VPA, intervals shorter than 30 s may disrupt the respiratory pattern, leading to an inability of the individual's cardiac output and oxygen transport efficiency to adapt to sudden increases in intensity (Wakefield and Glaister, 2009). Therefore, there is a correlation between the intensity and duration of intervals in PA and the individual CRF response. The study suggests that while interval exercise may provide a higher level of cardiorespiratory stimulation, training volume is a crucial factor in achieving this benefit. On the other hand, sedentary college students aim to improve physical activity efficiency by compressing training time. The study concludes that HIIT is the most effective way to achieve this goal.

The reason why HIIT can mediate higher levels of expression of CRF indicators in individuals than SIT with THR can be explained in terms of physiological basis. In our study, the mode of HIIT was set to 3 × 2, allowing subjects a longer period to adapt to the alternation between sprint and interval states. This led to adaptive changes in the myocardium, including thickening and structural adjustments of the ventricular wall, resulting in greater contractile force (Hanssen et al., 2011). At the same time, the process also increases the individual's left ventricular end-diastolic volume (LVEDV) and left ventricular end-diastolic pressure (LVEDP) to a greater extent than the SIT. This allows for more blood to be accommodated during each diastolic period, thereby increasing

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TABLE 3 Respiratory metabolism levels in different states/stages.

HIIT								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
TV (mL)	1090.31 ± 78.28	1497.17 ± 137.09						
RR (cpm)	31.21 ± 1.72	38.09 ± 1.71						
VE (mL/min)	34,528.95 ± 2808.75	52,712.14 ± 4203.38						
VO2 (L/min)	2.05 ± 0.26	2.68 ± 0.29	1.42 ± 0.3	1.83 ± 0.27	2.07 ± 0.32	2.23 ± 0.31	2.38 ± 0.27	2.38 ± 0.25
VCO2 (L/min)	1.96 ± 0.24	2.56 ± 0.24	1.32 ± 0.21	1.7 ± 0.26	2 ± 0.29	2.13 ± 0.32	2.29 ± 0.28	2.34 ± 0.21
RER	0.96 ± 0.08		0.94 ± 0.09	0.94 ± 0.1	0.97 ± 0.09	0.96 ± 0.11	0.97 ± 0.09	0.99 ± 0.1
VO2/HR	13.01 ± 1.61		10.64 ± 2.34	11.88 ± 1.99	13.17 ± 2.45	13.69 ± 1.97	14.14 ± 1.55	14.52 ± 0.95
	Pre	Inter	Post					
O2% (%)	19.48% ± 1.07	16.52% ± 1.97	12.62% ± 1.42					
CO2% (%)	3.20% ± 0.35	4.89% ± 0.69	5.78% ± 0.27					
SIT								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
TV (mL)	1150.9 ± 84.33	1429.3 ± 128.67						
RR (cpm)	31.69 ± 1.99	38.54 ± 2.42						
VE (mL/min)	37,118.64 ± 4519.29	52,782.57 ± 7201.28						
VO2 (L/min)	1.78 ± 0.2	2.41 ± 0.23	1.1 ± 0.24	1.47 ± 0.2	1.79 ± 0.2	1.99 ± 0.24	2.09 ± 0.25	2.21 ± 0.19
VCO2 (L/min)	1.6 ± 0.21	2.17 ± 0.24	0.98 ± 0.26	1.32 ± 0.23	1.61 ± 0.2	1.82 ± 0.25	1.94 ± 0.25	1.93 ± 0.22
RER	0.9 ± 0.06		0.89 ± 0.09	0.9 ± 0.07	0.9 ± 0.07	0.92 ± 0.09	0.93 ± 0.08	0.88 ± 0.08
VO2/HR	11.7 ± 1.56		8.26 ± 2.27	9.65 ± 1.37	11.56 ± 1.17	12.75 ± 1.55	13.25 ± 1.87	14.77 ± 2.22
	Pre	Inter	Post					
O2% (%)	20.04% ± 0.84	15.23% ± 2.13	11.82% ± 1.32					
CO2% (%)	3.11% ± 0.63	4.61% ± 0.72	5.77% ± 0.35					
THR								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
TV (mL)	1189.52 ± 138.23	1499.32 ± 163.79						
RR (cpm)	29.06 ± 1.23	34.15 ± 1.33						
VE (mL/min)	35,349.3 ± 4831.29	49,064 ± 5340.27						
VO2 (L/min)	1.82 ± 0.11	2.39 ± 0.23	1.28 ± 0.22	1.54 ± 0.21	1.78 ± 0.15	1.98 ± 0.14	2.12 ± 0.16	2.22 ± 0.21
VCO2 (L/min)	1.71 ± 0.17	2.32 ± 0.17	1.15 ± 0.32	1.45 ± 0.3	1.64 ± 0.24	1.85 ± 0.19	1.98 ± 0.16	2.19 ± 0.15
RER	0.93 ± 0.09		0.89 ± 0.18	0.94 ± 0.15	0.92 ± 0.12	0.93 ± 0.08	0.94 ± 0.04	0.99 ± 0.05
VO2/HR	11.2 ± 1.18		9.02 ± 2.1	9.35 ± 1.59	10.82 ± 1.71	11.94 ± 1.38	12.68 ± 0.98	13.39 ± 0.83
	Pre	Inter	Post					
O2% (%)	19.89% ± .94	14.68% ± 1.53	12.63% ± 1.07					
CO2% (%)	3.47% ± 0.67	4.92% ± 0.65	5.86% ± 0.35					

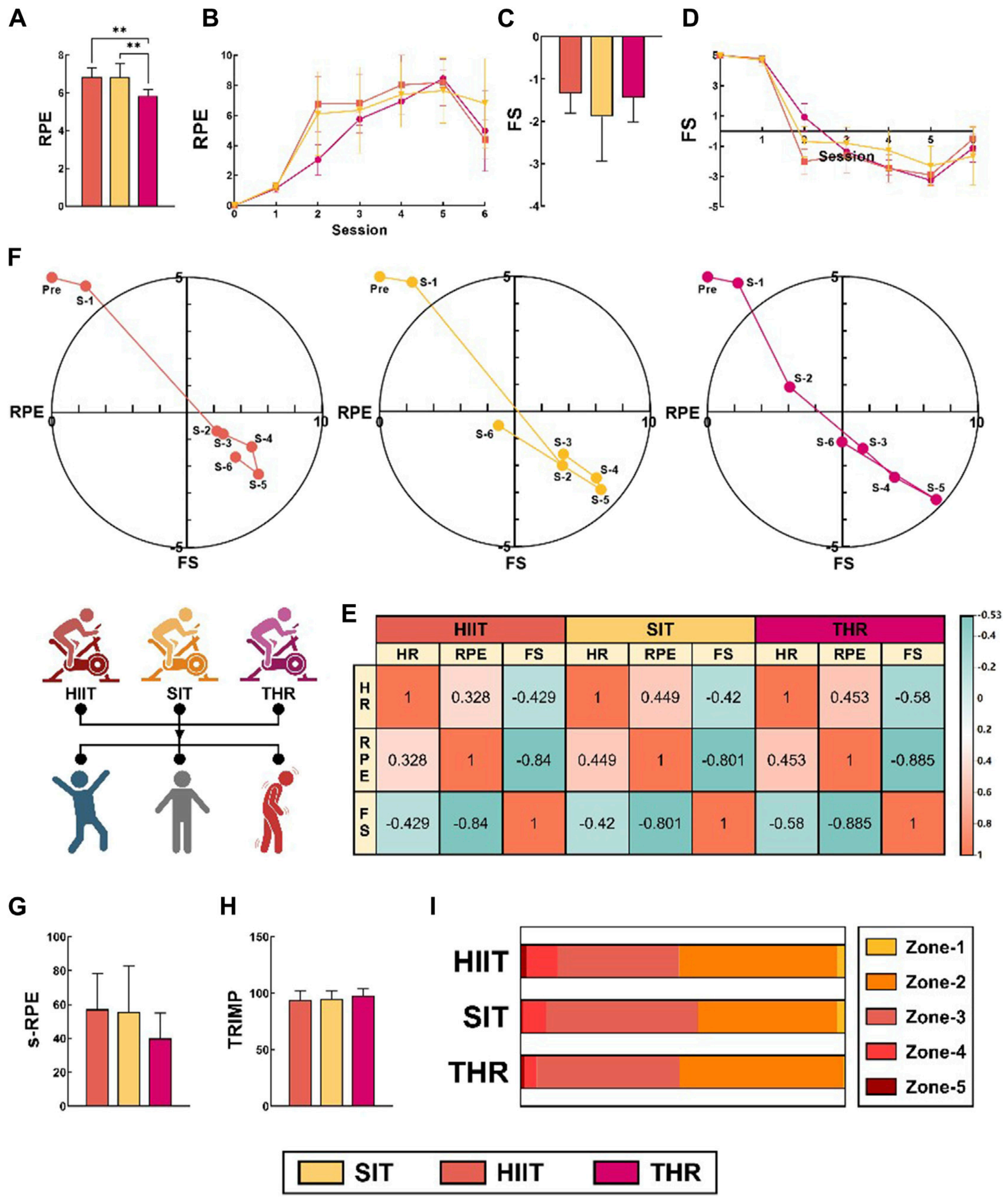

FIGURE 5
Exercise perception and training load condition in different states. Note: **(A–D)**: Expression levels and time domain characteristics of RPE and FS in different states; **(E)**: Correlations between exercise intensity, subjective fatigue, and exercise perception; **(F)**: DMM-based time-domain changes of subjective fatigue and exercise perception in different states; **(G, H)**: Expression levels of s-RPE with TRIMP in different states; **(I)**: Characteristics of the load distribution of different exercises in the intensity interval of Edward's TRIMP.

(CO) to meet the body's oxygen demand (Coates et al., 2023). Although there were no significant differences in HR among the three groups in this study, the SIT group had higher readings compared to the HIIT and THR groups. This is due to the sudden increase in sympathetic nervous system activity caused by the shorter and more intense stimulus in the SIT group. However, unlike HIIT, SIT does not allow enough time for the onset of sympathetic reactivation to mediate, resulting in insufficient myocardial adaptations. As a result, HR peaks and then rapidly declines after the sprint ends (O'Driscoll et al., 2018). Furthermore, the available evidence supports these findings. Huang compared the effects of single and periodic HIIT with THR on individual oxygen uptake levels by routine venous blood analysis and found that acute HIIT, compared with THR, increased erythrocyte osmotic deformability and aquaporin 1 (AQP1) levels more than THR, thereby mediating higher levels of oxygen transport efficiency and changes in myocardial adaptation. In contrast, after 6 weeks of intervention, HIIT attenuated the inhibitory effect of SB on

TABLE 4 Subjective perception and training load condition in different states/phases.

HIIT								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
RPE	6.86 ± 0.46	10 ± 0	1.25 ± 0.24	6.11 ± 2.8	6.35 ± 2.86	7.4 ± 2.16	7.65 ± 2.18	6.8 ± 2.99
FS	−1.34 ± 0.46	−4.18 ± 0.75	4.69 ± 0.29	−0.69 ± 0.55	−0.8 ± 0.75	−1.27 ± 0.57	−2.29 ± 0.76	−1.65 ± 0.68
Training load								
	Mean			HR-Zone of SHRZ (%)				
				Zone-1	Zone-2	Zone-3	Zone-4	Zone-5
TRIMP	94.17 ± 8			1.75% ± 1.55	9.71% ± 4.5	37.44% ± 11.18	48.65% ± 13.27	2.45% ± 4.26
s-RPE	57.27 ± 21.02							
SIT								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
RPE	6.84 ± 0.7	10 ± 0	1.2 ± 0.31	6.77 ± 1.85	6.8 ± 1.96	8.03 ± 1.99	8.2 ± 1.55	4.4 ± 1.33
FS	−1.89 ± 1.06	−3.71 ± 0.95	4.8 ± 0.16	−2 ± 1.02	−1.57 ± 1.07	−2.46 ± 0.88	−2.89 ± 1.03	−0.51 ± 1.83
Training load								
	Mean			HR-Zone of SHRZ (%)				
				Zone-1	Zone-2	Zone-3	Zone-4	Zone-5
TRIMP	95.09 ± 7.19			0.7% ± 0.37	7.2% ± 4.53	46.83% ± 12.79	42.84% ± 12.23	2.42% ± 3.8
s-RPE	55.71 ± 26.99							
THR								
	Mean	Peak	S-1	S-2	S-3	S-4	S-5	S-6
RPE	5.84 ± 0.34	9.33 ± 0.71	1.13 ± 0.24	3.04 ± 1.01	5.76 ± 0.43	6.93 ± 0.26	8.47 ± 0.58	4.98 ± 2.7
FS	−1.44 ± 0.57	−3.89 ± 0.6	4.78 ± 0.25	0.93 ± 0.7	−1.36 ± 0.71	−2.42 ± 0.42	−3.24 ± 0.61	−1.11 ± 0.98
Training load								
	Mean			HR-Zone of SHRZ (%)				
				Zone-1	Zone-2	Zone-3	Zone-4	Zone-5
TRIMP	98.12 ± 5.91			1.19% ± 0.72	3.91% ± 1.68	44.04% ± 20.59	50.65% ± 20.64	0.21% ± 0.47
s-RPE	40 ± 15							

erythrocyte membrane stability more than THR and increased stroke volume and umbilical artery flow velocity (Huang et al., 2019). Tsai also found that a single session of HIIT induced greater endothelium-dependent vasodilation and coronary perfusion in humans compared to SIT, while after 6 weeks of continuous intervention, participants in the HIIT group had higher densities of monocyte-derived endothelial progenitor cells, and hematopoietic stem cell densities were higher in participants in the HIIT group compared to SIT (Tsai et al., 2016). This also suggests that the training dose of HIIT induced an optimal cardiorespiratory response in individuals. On the other hand, mitochondrial function and thrombin regulation are also important mechanisms for improving CRF through HIIT. Chen found that HIIT can effectively improve neutrophil-derived microparticle (NDMP)-induced thrombin generation (TG) by down-regulating procoagulant factor expression during SB, thus reducing the risk of SB-induced thrombosis (Chen et al., 2015). Wu et al. demonstrated that increasing exercise intensity and adjusting training intervals can improve citrate synthase (CS) and succinate synthase. However, it is important to note that this may also increase the risk of SB-induced thrombosis. Wu et al. showed that increasing exercise intensity and adjusting training intervals can enhance the regulatory benefits of CS and succinate dehydrogenase (SDH) activities, as well as membrane potential (MP), which inhibits the elevation of matrix oxidant burden after SB. This suggests that HIIT improves mitochondrial bioenergetics and suppresses dynamic TG in platelets undergoing hypoxia more significantly than THR and SIT (Wu et al., 2017).

The study's second finding is that varying training volumes in VPA result in differences in exercise experience. When developing exercise prescriptions for SB college students, it is crucial to consider both the physiological effects of exercise forms and the individual's exercise experience. Research has demonstrated that having a positive experience is linked to an increased interest in exercise, while a negative experience can hinder the formation of exercise habits (Thøgersen-Ntoumani et al., 2023). In this study, it was observed that RPE was generally higher during intermittent exercise compared to continuous exercise, despite similar intensities. Although there was no statistically significant difference in FS readings, SIT resulted in the lowest level of exercise experienced by individuals. The time-domain plots of the two metrics showed no significant differences between the intermittent exercise groups, but significant differences were observed with continuous exercise. The DMM results indicate that individuals remain in the process of moving from vigor-pleasure to fatigue-loss during both HIIT and THR. However, during SIT, individuals cross over to the vigor-loss quadrant in the final stage. Therefore, hypothesis (III) cannot be accepted. These results validate previous studies. Stork conducted a comparison between the correlation of exercise form and exercise experience. The results showed that longer periods of time (>30 min) of THR triggered smaller increases in RPE and decreases in FS in SB undergraduates compared to short (20 min) HIIT (Stork et al., 2018). In contrast, Yusuf found that HIIT resulted in higher levels of RPE and PA enjoyment scale (PACES) when comparing the physical and mental responses to the two forms of exercise (Soylu et al., 2021). The study suggests that population differences may be the cause of this phenomenon. While both this study and Yusuf's study included college students, the inclusion criteria differed. Yusuf's study included recreationally active students, while the present study included sedentary college students with low subjective interest in exercise. The intensity-varying form of exercise requires a high level of physical fitness, which SB students may lack. In terms of interval exercise, Nicole compared three different volumes of HIIT and found that a smaller volume resulted in higher levels of fatigue and a lower experience. This is consistent with the results of this study (Olney et al., 2018).

Two psychological models can explain the phenomenon and psychological mechanisms. According to Noakes' central governor model (CGM), changes in muscle work during exercise are not determined by the metabolic factors of the muscle itself, but rather by the central nervous system (CNS). The CNS continuously integrates information from central, peripheral, and intracranial sensory afferents and actively adjusts the activity commands of motor units (alpha motor neurons and the skeletal muscle fibers they innervate) to achieve a constant load (Pompeu, 2022). During the process, THR experiences a constant load and therefore has a stable metabolic demand. On the other hand, SIT has a smaller volume and a more intensive transition between sprint and interval states, which places a greater demand on the CNS in terms of both muscular and metabolic activity. As a result, the supervisor experiences a decrease in fatigue and enjoyment. Marsden's muscle wisdom hypothesis, on the other hand, suggests that CNS adaptation to changes in peripheral myocyte contractile behavior leads to a decrease in motor unit discharge frequency during muscle fatigue (Garland and Gossen, 2002). In the present study, the same frequent changes in muscle work efficiency forced by SIT resulted in constant adaptation of the CNS, which led to the onset of exercise fatigue more easily. Therefore, the present study concluded that HIIT and SIT are not suitable for the development of exercise interest among SB university students.

The study's third finding revealed subtle differences in the physiological and psychological effects of training volume based on exercise loading. The results showed that, among the three sports, although there was no statistically significant difference between physiological load based on TRIMP and perceptual load based on s-RPE, THR had the lowest level of perceptual load and the highest physiological load based on the readings. Based on Edward's TRIMP load intervals, it is evident that HIIT has the highest percentage of being in the high load zone (Zone-5), while THR has the smallest percentage and the smallest interval span. Therefore, part of hypothesis (IV) can be accepted. This result also explains the superiority of HIIT over the other two in terms of physiological benefits. However, the lowest perceptual load of THR also suggests that it produces less psychological stress on the individual. An effective exercise prescription minimizes perceptual loads and increases physiological loads. Therefore, many studies have compared subjective and physiological loads. Tannath monitored the ITL of rugby players at different stages of the off-season. The study found that increasing the intensity of training caused both loads to rise, but that stabilized form training reduced the individual's s-RPE and perceptual load levels (Scott et al., 2022). Similarly, Jessica assessed load changes in ice hockey players over the course of a full season and found that the individual's TRIMP expression levels were not greater than on weekdays, but s-RPE was significantly higher than on training days (Bigg et al., 2022). Therefore, it is suggested that changes in both the type of exercise and the environment can lead to increased perceptual loads, which may negatively impact an individual's athletic performance. Additionally, Jill found that individuals had more consistent levels of fatigue expression during moderate to high intensity sustained exercise. However, TRIMP appeared to be higher in the HIIT group (Borresen and Lambert, 2008). The present study innovatively compared ITL between VPAs and found that training volume that is too intensive may not result in an increase in physiological load *versus* CRF benefits. The design of the training intervals affects the expression of perceptual load. Therefore, the study concludes that THR is more suitable for SB college students to acclimate during the initial period of exposure to sports. SIT and HIIT are suitable for the later period as an effective means to further improve the level of sports.

Based on these findings, previous evidence suggests that excessive training duration in SB adolescents inevitably leads to decreased exercise adherence. Therefore, studies have continued to examine the temporal characteristics of different exercise programs (Olney et al., 2018). In the present study, the duration of the three VPAs was approximately 20min per session, which is consistent with the goal of reducing training time to improve exercise efficiency. However, HIIT, SIT and THR still resulted in individual differences in physiological and perceived exertion due to differences in training volume. Based on the "Principle of Appropriate Load (Impellizzeri et al., 2022)", this study suggests that SB adolescents can determine their own maximum intensity thresholds based on RPE at the beginning of their exercise exposure (Coe and Astorino, 2024). Due to the weak training base and poor exercise motivation of this group, they may not be able to ensure the integrity of their training during over-intensity HIIT and SIT. THR may be an effective way to increase interest in exercise and improve exercise adherence. Second, according to the "progressive overload training principle (Khushhal et al., 2020)", the present study suggests that HIIT can be gradually incorporated into the training program and the intensity of the exercise can be increased after the exercisers have reached a certain level of baseline or exercise tolerance, for example, after one training cycle (2 months). Intensity to further promote the improvement of CRF and physiological adaptations. Finally, after a minimum of one and a half or volume cycles (3–4 months), SIT is used as an adjunct program to cross schedule with HIIT to enrich the workout, increase interest in the workout, and prevent the onset of central fatigue (Zarzissi et al., 2024).

Limitations and suggestions for future research

This study aimed to compare the acute effects produced by three groups of VPA of similar intensity on CRF indexes of sedentary college students by means of load monitoring, and to assess the differences between their subjective and objective reflections. The resolution and fine control of exercise were taken as the core of exploration. The goal was to determine the optimal exercise dose to enhance college students' CRF and cultivate their interest in exercise. However, this study still has limitations and deficiencies in terms of experimental design and training control.

The main objective of this study was to investigate whether differences in training volume during exercise of similar intensity affect the cardiac beat characteristics, respiratory metabolic status, and exercise experience of individuals. Additionally, the study aimed to assess the long-term post-exercise effects through acute effects. Strictly speaking, the experimental design of the present study, using cross-over repeated measures, is more reasonable. This approach better demonstrates the rigor of the experiment through the use of a homologous control. The initial experimental design of this study also adopted this scheme. However, the physical condition of the subjects and the arrangement of the actual intervention were not well controlled. During the homozygous controls, it was observed that the majority of subjects had less than 30% success and adherence to training after one to two single interventions (with a recovery interval of at least 72 h). As a result, only four out of the initial 10 completed the 3-sport intervention within 4 weeks, and the heterogeneity of results was too great to be included in the normal results. Therefore, the present study remedied this problem through a randomized controlled approach. Although this design requires a high number of samples, the present study included only 10 male participants in each group to minimize experimental error, as required.

The study focused on the acute effect of three exercise conditions on CRF metrics and subjective exercise experience in sedentary college students. The results indicate which form of exercise has the best overall improvement effect on individuals after a single session of VPA. If exploring the long-term effects of PA, the present study should be adapted to a longitudinal study with a long-term intervention for individuals. However, the experimental samples included in this study were comprised solely of undergraduate and graduate students with sedentary habits. As a result, this population had a low baseline level of exercise and interest in independent exercise, as well as class scheduling issues, which made it more difficult to organize long-term interventions. Additionally, adherence to homogeneous implementation was extremely low. However, this study is still in the process of testing the intervention in stages, with a limited number of subjects, 2–3 times a week. During successive interventions, it was found that due to the implementation of VPA, which requires a high level of physical fitness, the heterogeneity of the indicators during each monitoring was greater compared to MICT. This is why most studies have used MICT with HIIT as a control. However, this study focuses on the control of HIIT, SIT, and THR. Therefore, after careful consideration, we finalized the study design as a cross-sectional control of acute exercise.

Therefore, in the future, this study will focus on improving and optimizing the experimental design. This will involve implementing repeated cross-measurements under limited conditions to monitor individuals more precisely in different PAs. To improve the persuasiveness and rigor of the experimental results, this study will implement a longitudinal continuous intervention for existing subjects and strive to improve adherence by encouraging and adjusting the recovery interval. No new content has been added. This approach aims to comprehensively assess the optimal dose of PA to improve CRF and exercise interest in sedentary college students. It provides a more efficient and specific exercise prescription for non-pharmacological interventions to improve sedentary behavior.

Conclusion

(1) Differences in training volume at similar intensities mediate varying levels of respiratory metabolism. HIIT triggers the highest levels of VO2, VCO2, and OP, making it the most effective single-session stimulus for CRF. (2) The type of PA has a direct impact on an individual's PA experience. Intermittent PA can lead to excessive fatigue and reduce the perception of PA, which is not helpful in developing interest in PA among sedentary college students. (3) Differences in training volume at similar intensities cause variations in both subjective and physiological loads. Sustained exercise results in the lowest perceptual loads and the highest physiological loads, which are suitable for adapting to and establishing PA habits. (4) During the habit-establishment period, using a moderate amount of THR to cultivate interest and adaptive intensity, and the use of HIIT to enhance workout efficiency during the adaptation period, along

with SIT to reduce the monotony of training, may be an effective way to improve the cardiorespiratory fitness of sedentary college students and to establish PA habits.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The studies involving humans were approved by The Human Experimentation Ethics Committee of the School of Physical Education and Sport at Beijing Normal University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

HY: Data curation, Writing–original draft, Writing–review and editing. YG: Formal Analysis, Resources, Writing–review and editing. JL: Data curation, Formal Analysis, Supervision, Writing–review and editing. YF: Conceptualization, Data curation, Investigation, Writing–original draft. SJ: Funding acquisition, Investigation, Project administration, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Discrepancies in internal and external training load measurements during low-intensity biathlon training

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Purpose: This study aimed to differentiate external and internal training loads during on-snow biathlon training by adding an accelerometer-derived metric.
Methods: Eleven adolescent athletes were fitted with a combined heart rate (HR) and accelerometer to be worn during all training sessions. Duration, HR, training impulse (TRIMP), and average net force (AvF_{Net}) were used as training variables. All training was divided into either low-intensity training (LIT), or high-intensity training (HIT) based on reported intensity. The training was further categorized as training without any shooting practice (NS) or as a combination of skiing and shooting (COMB). Duration, HR, TRIMP, and AvF_{Net} were analyzed in a linear mixed model for the different training modalities.
Results: All training was similar in duration for LIT and HIT sessions ($p = .0521$) and NS and COMB sessions ($p = .988$). TRIMP did not differentiate between LIT or HIT training ($p = .350$) or for NS compared to COMB ($p = .298$). While AvF_{Net} decreased during COMB compared to NS during LIT sessions ($p < .001$) it remained similar during HIT training ($p = 1.00$).
Conclusion: The study's findings indicated that there were no notable differences in internal training load (TRIMP) when comparing various training intensities and modes. However, the type of training had a significant impact on AvF_{Net}, especially leading to a decrease during COMB sessions under LIT conditions. Incorporating an external load metric could offer a fresh approach when prescribing and evaluating training, providing deeper insights into the training load.

KEYWORDS
adolescent athletes, athlete monitoring, coaching, training organization, TRIMP

1 Introduction

Biathlon is an endurance sport that requires both fast cross-country skiing speed and good shooting accuracy (1). A biathlete must, accordingly, train on both parameters for successful performance. Shooting practice can be performed either as a stand-alone exercise or in combination with physical training, executed during both low-intensity training (LIT) and high-intensity training (HIT) (2, 3). Approximately 60% of all endurance training sessions are performed alongside shooting exercises (3). Biathlon physical training consists primarily of various endurance training modes depending on the training phase and access to snow (4, 5). Training modes are mainly divided into sport-specific training (roller skiing and on-snow-skiing, both in the classical and skating technique) and not sport-specific training (e.g., running and cycling).

Heart rate (HR) monitoring is the predominant tool for biathletes to prescribe and monitor training intensity. The methodology is based on the assumptions of a linear relationship to oxygen uptake (6, 7). Furthermore, training intensity is often categorized in predetermined HR training zones based on the percentage of the athlete's maximal HR (HR_{max}) (8). The aim is to accumulate a predetermined training volume in these zones with a supposed link to certain distinguishable metabolic domains. A recent paper (4) showed that successful biathletes accumulated approximately 18% more training volume during upper secondary school as juniors compared to less successful biathletes, with no difference in distribution between different intensity zones. However, HR monitoring as a tool for intensity steering and training quantification has been shown to poorly reflect training intensity during training in undulating or hilly terrains, which are often used as training grounds in biathlon. Several studies have shown that HR poorly reflects instantaneous work during skiing, with HR being highest during downhill skiing (9) or at the beginning of the following section after an uphill (10). HR has also been shown to reflect metabolic demand of various intensities during skiing inadequately (11), and is affected by environmental and psychological factors such as temperature and perceived effort during training (12).

In team sports, wearable accelerometers have been used to quantify the external training load and to improve the profiling of sport-specific demands, such as in ice hockey (13), football (14), and basketball (15). In endurance sports, studies have highlighted the discrepancy between internal intensity and instantaneous work (9, 16, 17) or external training load (18). These results suggest that accelerometer-based metrics may be a valuable tool for further improving the understanding of external training load in endurance sports. Consequently, the external training load for different biathlon training modes has never been investigated. Accelerometry-based metrics could seemingly provide an exciting insight into the multifaceted and intermittent nature of biathlon training. Hence, this exploratory study aimed to add an accelerometer-based metric for differentiating internal and external training loads in different reported training intensities during on-snow biathlon training, with and without shooting exercises, among late adolescent biathletes. It was hypothesized that the external load would be lower than the internal load during training sessions with shooting exercises compared to the training sessions without any shooting exercises.

2 Method

2.1 Participants

A cohort of eleven adolescent biathletes (male $n = 7$) and (female $n = 4$) age 19 ± 1 years of age at an upper secondary school with a biathlon profile volunteered to participate. All athletes were tier 3 athletes, according to the classification by McKay (17), and accustomed to systematized training and biathlon rifle carriage for at least one year. They received written and oral information about the study and gave their consent by signing an informed consent. The study was approved by the Swedish Ethical Review Authority (Dnr: 202202826-01).

2.2 Study design

Every athlete received a combined heart rate and triaxial accelerometer sensor (HR2, Movesense, Vantaa, Finland) and a smartwatch (Tic Watch Pro 3, Mobvoi, Hong Kong, China). The sensor was designed to be worn with a normal HR chest strap. HR and 104 Hz triaxial acceleration were sampled from the sensor to the watch through a smartwatch application (DCS, Kaasa Solutions GmbH, Düsseldorf, Germany). Before its initial use, all athletes performed a maximal running protocol to establish their HR_{max} on a treadmill (Rodby Innovations, Vänge, Sweden). The protocol involved running at a fixed speed (13 km/h for men and 11 km/h for females), with an increase in inclination of 2° for every 2 min, starting at 0°. The test was performed until voluntary termination by either stepping to the side of the treadmill or by signaling to the test leader. The athlete was secured by a safety harness, which was connected to an emergency switch to stop the treadmill in the event of falling. All athletes were instructed to wear the sensor and smart-watch during all their endurance-based training, including both the training at their upper secondary school and their unsupervised training time outside of school hours. The training sessions were categorized based on the reported session type using an online training diary (Maxpulse, Johan Bergman, Östersund, Sweden). The training was categorized as either skiing without shooting [no shooting (NS)] or as a combined shooting session alongside skiing [combination (COMB)]. Exercise intensity was prescribed to the athletes using a five-zone intensity scale (zone 1 55%–72% of HR_{max}, zone 2 72%–82% of HR_{max}, zone 3 82%–87% of HR_{max}, zone 4 87%–92% of HR_{max} and zone 5 92%–100% of HR_{max}). However, the training intensity was dichotomized in the present study into two categories. LIT was performed as continuous training within zones 1–2 (55%–82% of HR_{max}). All HIT were performed as interval-type sessions in zones 3–5 (>82% of HR_{max}). All data were collected over eight weeks (March–April) during the end of the competition phase on snow conditions as skiing only.

2.3 Data analyses

Accelerometer data were filtered in Matlab R2022b (Mathworks, Natick, MA, USA) using a fourth-order Butterworth bandpass low-pass filter with 0.1 and 15.0 Hz cut-offs for gravity and noise, respectively (9, 19) The external training load was calculated as the average net force (AvF_{Net}) as previously described elsewhere (15), Equation 1.

$$AvF_{Net} = BM \times \frac{\sum_{i=1}^{n}\left(\sqrt{a_{x_i}^2 + a_{y_i}^2 + a_{z_i}^2}\right)}{n} \quad (1)$$

Where AvF_{Net} is the average net force, BM is the body mass of the biathlete, a_x, a_y and a_z are the linear accelerations in the x, y, and z directions, and n is the number of samples. In order to determine the effect of different training modalities, the mass of the equipment (skis, rifle, clothing, hydration system etc.) was not included in the biathlete's AvF_{Net} calculation, as these parameters are subject to changes between sessions and even within a session. A modified training impulse (TRIMP), a mathematical derivation based on HR and duration, was used to calculate the internal training load (20, 21). The modified TRIMP was used because the weighting factor for each training zone in relation to HR, closely reflects the HR zones used in biathlon training. Individual HR response was used to calculate time in each training zone. Time spent below the threshold for zone-1 training was categorized as zone-0 training and was not allocated to LIT training and was therefore calculated as a separate intensity zone.

2.4 Statistical analysis

All statistical analyses were made in Jamovi (Jamovi, version 2.2.5, jamovi.org). Normal distribution was checked using Shaprio-Wilk test and by visually checking the residual plot. The only variable to be normally distributed was AvF_{Net}. A linear mixed model was used for all variables, due to the statistical robustness of both parametric and non-parametric variables (22). The linear mixed model was employed in a repeated measure design, incorporating both a within-subject factor and a between-group factor. The model was applied to examine the association of shooting factors (NS vs. COMB) and intensity training factors (LIT vs. HIT) in relationship to training duration, internal- and external training loads. Shooting factors and intensity factors were set as fixed factors, and biathletes as random effect, with random intercept across subjects. Each training intensity factor was set as the dependent variable. A new statistical model was made for each of the variables. The significance threshold was established at $\alpha < .05$. In the instances where the primary interaction demonstrated significance, a post-hoc comparisons were conducted with the Bonferroni correction. Effects size (ES) was calculated as omega square (ω^2) for all interactions in the analysis. The effect was considered small, medium, and large of values 0.001, 0.06, and 0.14, respectively (23).

AvF_{Net} data were presented as mean and standard deviation (SD), while non-normally distributed data was presented as median and interquartile range (IQR).

3 Results

A total of 82 training sessions and 8,075 minutes of training were collected. Due to some data loss, 79 sessions were included in the study for the analysis of AvF_{Net} and 78 sessions were included for TRIMP. Of the total 82 training sessions included in the study, 23% ($n = 19$) of the sessions were performed as HIT, and 24% ($n = 20$) were executed as COMB. There was no difference in session duration between LIT and HIT sessions (103 [86–124] minutes and 93 [88–109] minutes, respectively, $p = .0521$, ES = .0076) or between NS and COMB sessions (100 [89–120] and 96 [86–109] minutes, respectively, $p = .988$, ES = .0130). The distribution of time spent in zone-0 intensity during different training conditions was similar for LIT and HIT sessions (5.5 [1.7–11.8]% and 5.6 [2.3–9.6]%, respectively, $p = .554$, ES = .0084) and NS compared to COMB (5.4 [2.0–12.4]% and 6.9 [2.9–9.2]%, respectively, $p = .929$, ES = .0129). The median duration of each training condition is shown in Table 1.

3.1 Internal training load

TRIMP did not differentiate between LIT or HIT training (157 [120–202] A.U and 182 [168–222] A.U respectively, $p = .350$, ES = .0016) or for NS sessions compared to COMB (150 [117–205] A.U and 178 [163–216] A.U respectively, $p = .298$, ES = .00052). There was no interaction effect of intensity and shooting variables on TRIMP ($p = .975$, Figure 1).

3.2 External training load

There were no differences in external training load between LIT and HIT (267 ± 42 N and 271 ± 44 N, respectively, $p = .301$, ES = .0010) while AvF_{Net} was greater during NS compared to COMB (276 ± 38 N and 242 ± 44 N respectively, $p = .015$, ES = .0619). While external load decreased during COMB compared to NS during LIT sessions (Figure 1) $p < .001$, ES = .2163) it remained similar during HIT training ($p = 1.00$, ES = .0468, Figure 1).

4 Discussion

Based on the lack of knowledge on biathlon training loads, the current study aimed to investigate whether an accelerometer-derived external load measure could be an integrated tool for biathletes to better understand the demands of biathlon on-snow training that are not reflected with HR monitoring. The main

TABLE 1 Median duration spent in either intensity of zone 0, low-intensity training (LIT), and high-intensity training (HIT) with (COMB) and without (NS) shooting practice.

	LIT-NS	LIT-COMB	HIT-NS	HIT-COMB
Session duration (min)	108 [92–124]	93 [85–105]	92 [87–105]	100 [90–110]
Zone-0 duration (min)	4 [2–15]	6 [4–8]	5 [2–12]	9 [3–10]
LIT duration (min)	85 [58–103]	59 [48–72]	57 [53–60]	59 [49–65]
HIT duration (min)	4 [0–21]	25 [20–33]	29 [18–35]	36 [30–37]

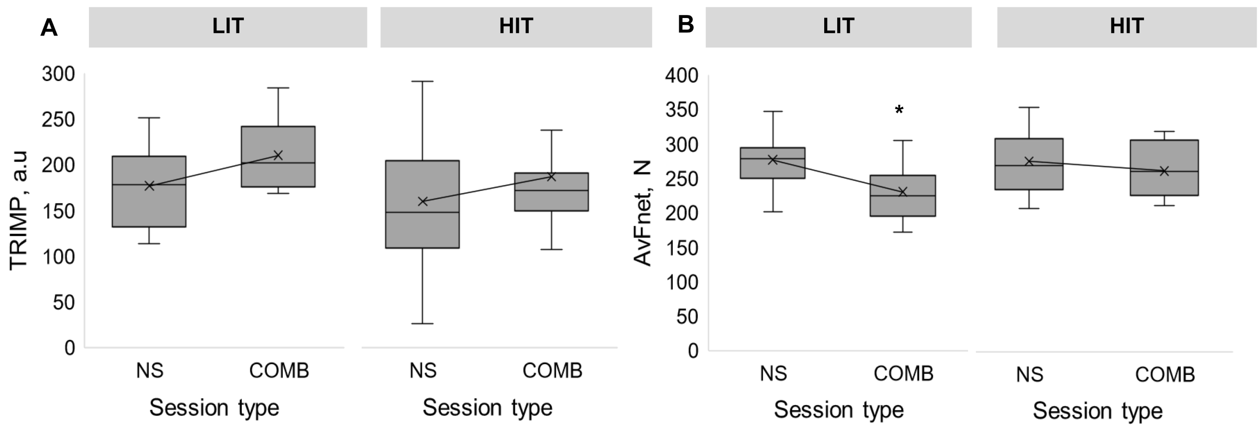

FIGURE 1
Distribution and median internal (A) and external (B) load for session type and intensity. *Significant difference between NS and COMB sessions. LIT, Low-intensity training; HIT, High-intensity training; NS, No shooting; COMB, Combination training of physical and shooting practice. Values are presented as median and interquartile range [IQR].

finding was that TRIMP remained similar for both LIT and HIT sessions independently of NS or COMB. Further findings of the study were that the external training load during LIT with COMB was lower compared to LIT with NS. This highlights the potential to measure external load as a supplementary metric during on-snow biathlon training sessions.

4.1 Internal load and duration

To date, HR monitoring is the primary tool for prescribing and monitoring intensities during biathlon training. The study findings indicate that HR as a tool for evaluating total training load overestimates the training load that a junior biathlon is affected by during on-snow skiing. This is visualized by the difference in external load during LIT sessions, not previously examined in a long-term training setting.

Previous biathlon studies did not show an effect on the HR response during rifle carriage compared to skiing without the rifle in laboratory settings (24, 25) or in an outdoor setting (9). Such data are in line with the findings of the present study, in that a modified TRIMP does not differ between shooting conditions (NS vs. COMB) when the duration of the training sessions is equal. The equal training duration between different training conditions and reported training intensities may indicate that coaches at upper secondary schools are limited by the available training time to balance the school system. Since the school must ensure that student–athletes achieve a sufficient level in both their schooling and sporting performance, there is a delicate balance involved in budgeting the time needed to manage both tasks over the long term. This emphasizes the notion that the sessions are not optimally planned to train on a desired training variable but are rather based on available training time, which is similar between training sessions.

Furthermore, there was no difference in TRIMP between the LIT and HIT sessions, which is potentially explained by the structure of LIT vs. HIT sessions. LIT sessions accumulate a relatively lower HR response over a greater part of the training session before resting (e.g., for drinking or shooting, etc.), while HIT is performed with a greater HR response over a shorter period (usually between 4 and 8 min, depending on the interval session) before a longer rest where the HR is reduced to the LIT zone. However, the data show that even during LIT sessions, HR fluctuates and increases well into the training zones associated with HIT. Previous studies have shown that HR remains elevated when activity alternates between moderate and more intense workloads (26), potentially induced in the present study by the undulating terrain. The result suggests that the ability to differentiate training load based on HR response is not satisfying for on-snow biathlon training.

Different TRIMP models use different mathematical equations to quantify the accumulated training load (21). TRIMP models that use a zone-divided approach justify doing so to gain a more accurate reflection of the account of high-intensity aerobic and/or anaerobic work that may not be shown by the use of average HR or HR-reserve TRIMP methodology. In the present study, a substantial amount of time was recorded in a zone below LIT definitions; zone-0, which would not be considered training intensity and therefore not included in the total TRIMP value. However, more data are needed to show how and when zone-0 time is accumulated; e.g., at what speeds or at which moments during training. Is an athlete considered to be training if their HR corresponds to LIT intensity, even if they are not moving? Conversely, are they not training if they are moving but have an HR response that does not exceed the LIT intensity threshold? The more philosophical question of whether an athlete is undergoing training during zone-0 training should be centered in further research.

4.2 External load vs. exercise intensity

The use of an accelerometer-derived metric during training provides insight into biathlon training not visible with HR measures. The data presented showed, for the first time, that during LIT- COMB, junior biathletes accumulate significantly lower external load compared to LIT-NS, even though the training duration is similar. This could potentially be caused by several factors.

Since the accelerometer-derived metric is a result of bodily acceleration and de-acceleration, the major cause of a lower AvF_{Net} is likely because of an altered movement during COMB training and the training structure of COMB sessions. Carrying the rifle during skiing has previously been shown to decrease the vertical distance of the upper body while also altering the range of motion in the upper body (27). Previous research also suggests that more force needs to be produced by the lower body instead of the upper body when skiing with the rifle compared to without (25). That factor could explain why the altered movement of the upper body (where the sensor is placed) is impaired, resulting in a lower AvF_{Net}. The placement of the sensor should be recognized as a factor in the outcome of this study. One study showed that the AvF_{Net} was not different between skiing with or without a rifle during a simulated race when the sensor was placed at the lower spine (9), with less registration of the movement by the upper body. Sensor position must be kept in mind when comparing studies and results using accelerometer data. Furthermore, the training structure could be a potential factor for the lower external load since LIT-COMB often includes more series of shooting drills compared to HIT-COMB. This consequently leads to more time spent standing still while shooting and while refilling ammunition. Implicitly, this would indicate more standing still compared to other types of training sessions, but without compensating by increasing training duration to equal the time spent moving. Coaches should be aware that training administrations could affect the training load's potential outcome. Future studies should take different training regimes into consideration. The HIT session did not show any differences in external load when comparing NS and COMB, probably due to the similarity in training structure, with similar warm-up, interval- and rest durations.

4.3 Limitations

The present study consists of a relatively small sample size. All athletes were attending the same upper secondary school; therefore, it cannot be excluded that data were affected by coaching philosophy and geographical training ground. Finally, no further measurement or variable was included that could explain the differences in external training load between the types of sessions, such as speed or perceived effort.

Future studies are encouraged to include a larger population of biathletes and to sample training variables over a greater range of activities for a more comprehensive understanding of the training load in biathlon training.

4.4 Practical implications

The complementary usage of an accelerometer-derived metric during physical training seems to be a valuable tool for highlighting the difference in internal and external training load during on-snow skiing for biathletes. Using an external load metric could provide a new tool for biathlon coaches and biathletes when prescribing and analyzing training. A more comprehensive picture of the total training load allows for future training session adjustments and better training plan cohesion. Athletes and coaches who use TRIMP as the only metric for long-term training load monitoring need to be aware of the uncertainty in the TRIMP method due to the fluctuating HR response during skiing. This proves the difficulty for adolescent athletes to train solely in a prescribed intensity zone during skiing and rather a pragmatic attitude of using a strict HR-based intensity zone is more appropriate.

5 Conclusion

In conclusion, the study found no significant differences in internal training load (TRIMP) across different training intensities and modalities. However, external training load (AvF_{Net}) was significantly influenced by the type of training, particularly showing a reduction during combined sessions under LIT conditions. These findings suggest that while internal load remains stable, external load is more sensitive to the combination of training modalities, emphasizing the need to consider both internal and external metrics when designing and evaluating training programs.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Swedish Ethical Review Authority (Dnr: 202202826-01). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin because in line with the Swedish Ethical Review Authority guidelines, research participants who are 15 but not yet 18 years old should be informed about the research and provide their consent themselves if they understand what the research entails for them. Only when young people between 15 and 18 years old have not reached a level of maturity to understand what the research entails for them, it becomes relevant to turn to their guardians.

Author contributions

AK: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft, Writing – review & editing. MS: Data curation, Formal Analysis, Supervision, Writing – original draft, Writing – review & editing. GB: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Relationship between the contact load and time-loss injuries in rugby union

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Objective: Quantifying and managing the matches and training loads of players is important for injury prevention. As rugby union is a full-contact sport and frequent contact injuries occur, it might also be important to quantify and manage players' contact loads. This study aimed to clarify the relationship between contact load and injury incidence in elite rugby union players.
Methods: Forty-eight elite rugby union players (27.0 ± 3.5 years) in Japan were monitored during one season (8 months). The contact load, an index of training load, was evaluated as collision count and collision load measured using a global positioning system device, and then calculated using the acute: chronic workload ratio (ACWR) based on the exponentially weighted moving average (EWMA). The association between the EWMA-ACWR of contact load and injury incidence was analyzed using generalized estimating equations.
Results: Of the 58 injuries during one season, 70.7% were contact injuries. Collision counts and collision load calculated by EWMA-ACWR were associated with the risk of injury ($p < 0.01$ both), with the odds ratios were 4.20 [95% confidence interval (CI): 1.74–10.11] and 4.44 (95% CI: 1.95–10.13), respectively.
Conclusion: Contact load calculated using EWMA-ACWR was associated with injury in elite rugby union players.

KEYWORDS
contact sports, injury, monitoring, exponentially weighted moving average, acute: chronic workload ratio, GPS

1 Introduction

Sports injuries are common among athletes. Notably, time-loss injuries prevent players from participating in future training or match play (1), thereby affecting team success in team sports (2, 3). Therefore, strategies to reduce injuries and maximize player availability are crucial. The risk factors for injury incidents are complex and multifactorial and are classified as non-modifiable (e.g., history of previous injury, age, sex, and genetic predisposition) or modifiable (e.g., aerobic fitness, strength, and exposure to loads) (4). Controlling modifiable risk factors is key to preventing injuries in athletes.

A global positioning system (GPS) device was used to measure the overall distance and speed during training sessions or matches (5). Some studies used the acute:chronic workload ratio (ACWR) to quantify and control match and training load in various sports and demonstrated an association between ACWR and injury incidence (6–10). ACWR is the ratio of the acute load to the chronic load, where the short-term load (e.g., the last week) is defined as the acute load and the long-term load (e.g., the previous four weeks) as the chronic load (11). In cricket, Australian football, and rugby league, an ACWR training load of 0.8–1.3 was reported to indicate a low risk of injury, and ACWR > 1.5 was associated with a high risk of injury (11). This theory has been criticized in several papers by Impellizzeri et al., who noted that RA-ACWR is inherently less predictive and introduces statistical artifacts in 2019 and 2021 (12, 13). However, ACWR remains an influential metric in sports science and is used by practice and strength-and-conditioning coaches due to its simplicity and convenience (6). A new method for calculating ACWR, the exponentially weighted moving average (EWMA), which calculates the moving average by assigning a large weight to the most recently undertaken load (14), was recently proposed. Compared with the conventional calculation method of rolling average ACWR (RA-ACWR), EWMA-ACWR showed a greater association with the risk of injuries (15–18).

Rugby union, which is a form of rugby played in teams of fifteen (19), has one of the highest incidences of injury among all professional team sports, with 91 and 2.8 injuries per 1,000 player hours at matches and training, respectively (20). Collisions have been shown to be a significant contributor to the incidence of injuries, with over 60% of all injuries during matches occurring during contact play (20). World Rugby, the international governing body of the rugby union, proposed contact load guidelines in 2021 to manage and limit contact practice time from the perspective of injury prevention (21). Contact load has been evaluated using contact intensity and volume in matches and training (21). Recently, novel GPS devices that enable quantification of the contact intensity and volume have been developed (22) and verified to have a high correlation with video analysis for events identified as collisions (23). As the GPS device can also monitor acute and chronic loads of contact intensity and volume, using EWMA-ACWR in conjunction with novel GPS devices might clarify the risk of injury in rugby union players. Previous studies of rugby union have predominantly focused on non-contact variables such as overall distance measured by GPS (15, 24). However, these studies not sufficiently take into consideration the characteristics of rugby union, which contact plays a critical role, the relationship between the quantification of contact intensity and volume and risk of injury in rugby union remains insufficiently explored. Therefore, this study hypothesized that there is an association between contact load and the risk of injuries in rugby union players, and aimed to investigate the association between the contact load evaluated using GPS devices and time-loss injury in elite male rugby union players by calculating EWMA-ACWR.

2 Materials and methods

2.1 Study design

This retrospective, observational study used load data evaluated from GPS devices and injury records of 48 elite male rugby union players (mean [standard deviation]; age: 27.5 [3.1] years, height: 180.7 [7.6] cm, body weight: 97.2 [11.8] kg) who belonged to Japan Rugby League One, Japan's professional three-tier rugby union competition (Table 1). All participants were informed of the purpose, methods, procedures, and risks of this study and provided written informed consent. This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee for Human Experiments of Juntendo University (No. 2021-115). The observation period covered one season and the pre-season period between August 30, 2021, and May 8, 2022.

2.2 Load data in matches and training

Load data during matches and field-based training sessions were obtained using a GPS device (STATSports Apex, Northern Ireland) (25, 26). This device collected data from a GPS, accelerometer, magnetometer, and gyroscope at frequencies of 10, 952, 10, and 952 Hz, respectively. The GPS device was placed in the small pocket of a specially designed vest and worn on the upper back, that is, over the thoracic spine, between the left and right scapulae. The players wore the same device during the study to eliminate inter-unit variability and errors. Data measured by GPS devices were used to calculate the collision load as contact load, collision count, distance, and high-speed running using STATSports Sonra (STATSports). Collisions were detected by changes in the axis orientation and impact force of >8 g and calculated using a weighted algorithm combining the maximum velocity into the collision, peak impact force, and collision duration (22). Distance and high-speed running data were collected using GPS at a 10 Hz rate; high-speed running was defined as the distance covered at speeds >5.5 m/s (26).

2.3 Data processing

ACWR of the collision count, collision load, distance, and high-speed running were calculated for each participant as load indicators in matches and training. The calculation period was 7 days for the acute load and 28 days for the chronic load. In this study, acute and chronic loads were calculated using EWMA. EWMA for any given day was calculated as follows: $\text{EWMAtoday} = \text{Loadtoday} \times \lambda a + ((1 - \lambda a) \times \text{EWMAyesterday})$, where λ_a is a value between 0 and 1, which represents the degree of decay. λ_a was calculated as $2/(N + 1)$, where N is a 7-day (acute) or

TABLE 1 Demographic details of the study participants.

	Total (n = 48)	Forwards (n = 25)	Backs (n = 23)
Age, years	27.5 (3.1)	27.4 (3.3)	27.7 (3.7)
21–25	17 (35.4%)	9 (52.9%)	8 (47.1%)
26–30	20 (41.7%)	11 (55.0%)	9 (45.0%)
31–35	11 (22.9%)	5 (45.5%)	6 (54.5%)
Height, cm	180.7 (7.6)	183.5 (8.1)	177.6 (5.4)
Body weight, kg	97.2 (11.8)	106.0 (7.2)	87.2 (7.1)

Data are expressed as number (%) or mean (standard deviation).

28-day (chronic) period. Acute EWMA was then divided by chronic EWMA to provide a single EWMA-ACWR value (14).

2.4 Definition of injury

Injury was defined as physical discomfort that occurred during training or a match that prevented full participation in a training session or match and was diagnosed and classified by the team medical staff according to the consensus statement of the International Rugby Board in 2007 (1). Furthermore, the severity (number of days unavailable for training and/or matches), nature of the injury (contact or non-contact), and session in which the injury occurred (training or match) were categorized as previously reported (1).

2.5 Statistical analysis

Odds ratios with 95% confidence intervals (CI) were calculated using multiple logistic regression analysis to determine the association between each ACWR and injury occurrence. As this study included repeated ACWR data during the observation period, generalized estimating equations (GEE) were used to model the population-averaged effects of all data. At first, athlete as the subject variable, date of measurement as the within-subject variable, to take into account the correlation between repeated observations of injury incidence within subjects, an autoregressive correlation matrix. The calculate model included injury occurrence (injury/no injury) as the dependent variable, ACWR for each load as the independent variable, position (forward/back), season (pre-season/in-season), and age as confounders. All statistical analyses were performed using SPSS Statistics version 25 (IBM, New York, USA), and statistical significance was set at $P < 0.05$.

After that, the incidence of injury from each ACWR value based on the above results indicated using the following formula (15).

Injury incidence on each ACWR value (per player day) $= \frac{\exp(\text{intercept} + \text{parameter estimate} \times \text{ACWR})}{1 + \exp(\text{intercept} + \text{parameter estimate} \times \text{ACWR})}$.

The above calculation was for injuries in forward players.

To calculate the injury incidence in back players, the effect of position was added to the equation as follows: $\frac{\exp((\text{intercept} + \text{parameter estimate} \times \text{ACWR}) + \text{position parameter estimate})}{1 + \exp((\text{intercept} + \text{parameter estimate} \times \text{ACWR}) + \text{position parameter estimate})}$.

3 Results

The demographic characteristics of the participants are presented in Table 1. Table 2 shows the total number of injuries, nature of the injury, and session in which the injury occurred. During the cumulative observation period of 9,570 player-days, 58 injuries occurred (5.18 injuries/1,000 player-hours), and the cumulative number of days lost was 1,004 (10.5%). All were categorized as trauma, and 70.7% were contact injuries.

The association between each EWMA-ACWR and the risk of injury is shown in Table 3. In all regression analysis models, age, position, and season were not associated with the risk of injury.

TABLE 2 Total number and nature of injuries according to the session.

	Total	Injury/1,000 player-hours (95% CI)	Contact injury	Non-contact injury
Total number of injuries	58	5.18 (3.9–6.5)	41 (70.7%)	17 (29.3%)
In matches	34	66.7 (43.9–89.4)	29 (85.3%)	5 (14.7%)
In training	24	2.34 (1.42–3.25)	12 (50.0%)	12 (50.0%)

Data are expressed as number (%) or median (95% CI).

The collision count and collision load calculated by EWMA-ACWR were associated with the risk of injury ($p < 0.01$ for both; Figures 1, 2); the odds ratios were 4.20 (95% CI: 1.74–10.11) and 4.44 (95% CI: 1.95–10.13), respectively, for 1 EWMA-ACWR increase in contact load. Distance and high-speed running evaluated by EWMA-ACWR were not associated with the risk of injury (distance: $p = 0.54$; Figure 3; high-speed running: $p = 0.32$; Figure 4).

4 Discussion

In the present study, we observed 58 injuries (5.2 injuries/1,000 player-hours), 70.7% of which were contact injuries. We calculated the contact load (collision count and collision load) in addition to distance and high-speed running during the study period. We demonstrated that the collision count and collision load evaluated using EWMA-ACWR showed a positive association with the risk of injury in elite rugby union players. To date, the International Olympic Committee recommends using ACWR to monitor injury risk in many sports (6). If the acute load exceeds the chronic load (i.e., if the acute load increases rapidly and fatigue occurs, or if training in the previous four weeks has been insufficient to improve fitness), it has been reported to increase the risk of injury in various sports (6–10). In these reports, non-contact variables, such as sRPE, overall distance measured by GPS, and distance during high-speed running (27–30), were used as training loads. The sports in these studies were soccer, field hockey, and Gaelic football. Generally, the proportion of contact injuries in sports (31–34) is less than 40%, which is lower than that of rugby union, in which the proportion of contact injuries is more than 75% (20). In rugby union, most injuries were reported to occur during contact play, including tackling (23.0%), being tackled (22.8%), and collision (14.2%) (20), and 70.7% of injuries in the present study were also classified as contact injuries. Therefore, monitoring the injury risk in rugby union should also be considered along with contact load.

This study used EWMA-ACWR to investigate the association between contact load and injury incidence. Although the conventional calculation method of RA-ACWR is easier to calculate, as it equally weighs all load data included in the calculation (35, 36), it has been reported that RA-ACWR is inherently less predictive and introduces statistical artifacts (12, 13). On the other hand, EWMA proposed by Williams et al.

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TABLE 3 Association between each EWMA-ACWR and the risk of injury.

	Intercept	ACWR for each load				Position			Season		
		Parameterestimate	Std. error	Odds ratio	95% CI	Parameter estimate	Odds ratio	95% CI	Parameter estimate	Odds ratio	95% CI
Collision counts	−10.09	1.43	0.45	4.20	1.74–10.11	0.64	1.89	0.47–7.59	0.32	1.37	0.24–7.93
Collision load	−10.12	1.49	0.42	4.44	1.95–10.13	0.64	1.89	0.50–7.13	0.51	1.67	0.33–8.51
Distance	−9.29	0.61	0.99	1.83	0.26–12.75	1.01	2.74	0.30–25.07	0.99	2.70	0.12–63.17
High-speed running	−9.08	0.49	0.49	1.63	0.62–4.24	0.45	1.56	0.47–5.23	0.15	1.16	0.27–4.94

Position is the odds of injury in backs compared to forwards.
EWMA, exponentially weighted moving average; ACWR, acute:chronic workload ratio; CI, confidence interval.

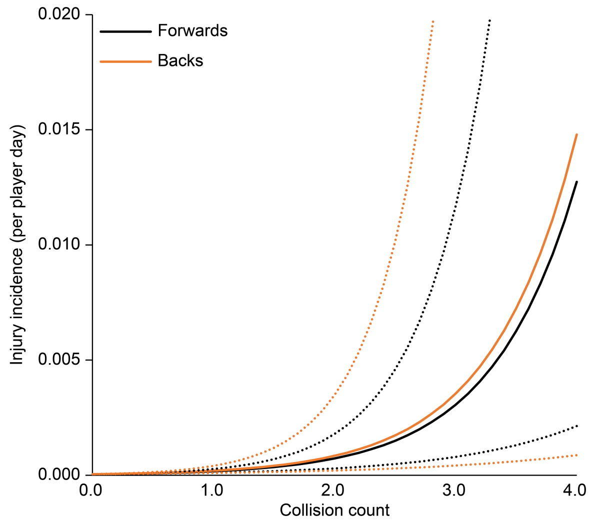

FIGURE 1
Relationship between collision count (EWMA-ACWR) and injury incidence (per player day).
Note: Data are expressed as mean (solid line) and standard error (dotted line). EWMA, exponentially weighted moving average; ACWR, acute:chronic workload ratio.

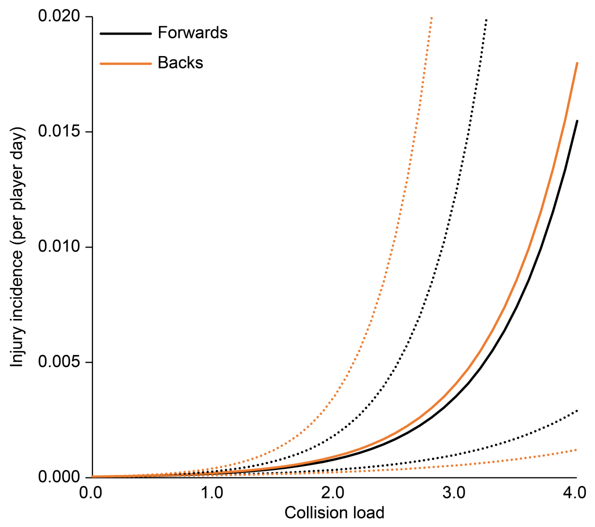

FIGURE 2
Relationship between collision load (EWMA-ACWR) and injury incidence (per player day).
Note: Data are expressed as mean (solid line) and standard error (dotted line). EWMA, exponentially weighted moving average; ACWR, acute:chronic workload ratio.

(14) is calculated by weighing more recent loads and considering the influence of more recent loads on the occurrence of injury. Several studies have investigated the relationship between match and training load (not contact load, but sRPE, distance, and high-speed running) and injury incidence using RA-ACWR and EWMA-ACWR and showed that EWMA-ACWR was more associated with injury than RA-ACWR (15–18). Therefore,

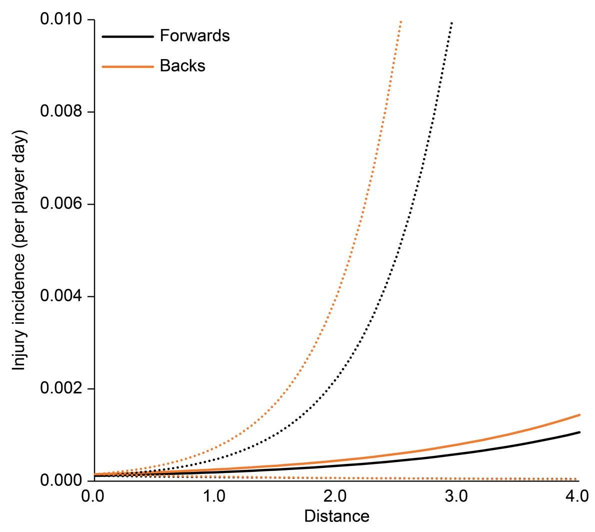

FIGURE 3
Relationship between distance (EWMA-ACWR) and injury incidence (per player day).
Note: Data are expressed as mean (solid line) and standard error (dotted line). EWMA, exponentially weighted moving average; ACWR, acute:chronic workload ratio.

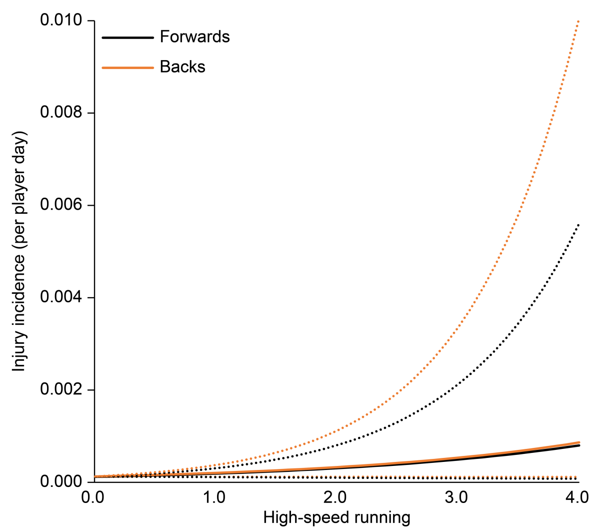

FIGURE 4
Relationship between high-speed running (EWMA-ACWR) and injury incidence (per player day).
Note: Data are expressed as mean (solid line) and standard error (dotted line). EWMA, exponentially weighted moving average; ACWR, acute:chronic workload ratio.

monitoring the EWMA-ACWR of collision load and/or collision count in training and matches might be an effective method to prevent the risk of injury.

This study indicates that the EWMA-ACWR of the contact load measured by GPS devices is associated with the risk of injury in an elite rugby union team. However, this study had some limitations. First, collision metrics were detected by changes in the axis orientation and by an impact force >8 g using a GPS device (STATSports Sonra; STATSports Group Limited, Northern Ireland) and calculated by a weighted algorithm combining the maximum velocity into the collision, peak impact force, and collision duration. However, the details of this algorithm are not available. In addition, this study used position, season, and age as confounders; other risk factors, such as internal load (6), also need to be considered. Furthermore, this study only considered loads that could be measured using GPS devices. Therefore, indoor training, such as gym training, was not included as a training load. Next, because this study evaluated the acute load for 7 days and the chronic load for 28 days, the first 27 measuring days were excluded from the ACWR calculation period. Therefore, it was impossible to assess the first month after the start of training. In addition, the relationship between ACWR and injury may fluctuate when different calculation periods are used for acute and chronic loads (18). Moreover, there is increasing evidence of the limitations of RA-ACWR (12, 13). Similarly, although the EWMA method is commonly used, it is not without its limitations (37, 38). The EWMA-ACWR measurement method is also not standardized; elements such as calculation methods, time-window settings, and analysis methods have not been established. Furthermore, although ACWR has been published in consensus statements by the International Olympic Committee (6) and is widely used worldwide, the consensus statement may be updated in the future. Therefore, future analysis using quantification methods other than EWMA-ACWR (e.g., absolute contact load values and cumulative rolling sums) might be necessary to clarify the relationship between contact load and time-loss injury. Next, this study analyzed the association between ACWR and all injuries during only one season. Future studies need to clarify the relationship between contact load and injury, separated by the nature of the injury (contact/non-contact), severity, and situation (training/match) based on several seasons. Lastly, in the future, conducting intervention studies to determine whether adjustment of contact load reduces the incidence of injury will likely show that contact load is an important factor in injury prevention in rugby union.

In conclusion, the contact load calculated using the EWMA-ACWR was associated with time-loss injury in elite rugby union players. Thus, this study showed as rugby union is a full-contact sport and frequent contact injuries occur, preventing injury in rugby union players also requires monitoring and management of the contact load. Based on this study, coaches and strength and conditioning coaches could possibly make strides in player safety and performance in practice.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Ethics Committee for Human Experiments of Juntendo University. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

YI: Conceptualization, Investigation, Writing – original draft. YS: Writing – original draft, Writing – review & editing. MN: Writing – review & editing. SN: Writing – review & editing. YS: Formal analysis, Methodology, Writing – review & editing. YT: Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Research on the effect of post-activation potentiation under different velocity loss thresholds on boxer's punching ability

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This study was conducted in accordance with the principles of velocity-based training theory, with the objective of investigating the effects of post-activation potentiation (PAP) induced by different velocity loss (VL) thresholds (10% vs. 20%) on the punching ability of boxers. In addition, the aim was to determine the velocity loss thresholds and time nodes that produced the optimal activation effect. Twenty-four male elite boxers were randomly assigned to three groups: CON, 10 VL, and 20 VL. All subjects in the three groups underwent an activation intervention involving an 85% of the one-repetition maximum (1RM) squat, with 6-8 repetitions performed in the CON. The number of repetitions in the 20%VL and 10 VL was determined based on the velocity loss monitored by the GymAware PowerTool system. Four time points were selected for observation: the 4th, 8th, 12th and 16th minutes. These were chosen to test the subjects' punching ability. The results demonstrated that activation training at different VL induced a post-activation potentiation in boxers, improving punching ability bilaterally and to a greater extent than in the CON. The dominant side demonstrated the greatest efficacy at the 12th minute under the 20% velocity loss threshold, while the non-dominant side exhibited the greatest efficacy at the 8th minute under the 10% velocity loss threshold.

KEYWORDS

boxing, punching ability, post-activation potentiation, velocity-based training, velocity loss

1 Introduction

Boxers must possess excellent punching ability in order to deliver high-quality and effective punches (Loturco et al., 2016). A warm-up based on post-activation potentiation (PAP) may have a superior optimisation effect on boxers' punching ability, thus further improving performance. In the existing studies, the activation training protocols have used the percentage of the one-repetition maximum (1RM) as the loading intensity and a fixed number of repetitions as the loading volume (Guo et al., 2022). However, such programmes ignore individual differences in athletes and fluctuations in physical status. Due to pre-competition physiological and psychological changes, as well as sleep status, fatigue recovery, nutritional supplementation and other factors, the 1RM of athletes is not stable and it is difficult to determine the optimal number of repetitions (González-Badillo and Sánchez-Medina, 2010). This makes it impossible to precisely control the load intensity and load volume during the induction of the PAP, which is not conducive to the production of an optimal PAP, or even fatigue, which is counterproductive (Dorrell et al., 2020; Liao et al., 2021). Therefore, further investigation is required into the loading arrangement for inducing the PAP.

Some researchers have attempted to investigate the regulation of strength training loads using movement velocity as a point of departure. Their findings indicate that the load intensity at the time of completing the movement was significantly correlated with the movement velocity in a variety of types of strength training (Pereira and Gomes, 2003; Weakley et al., 2021), and significantly correlated with the percentage of velocity loss (VL) (González-Badillo et al., 2006; Pareja-Blanco et al., 2017b). The amount of load in strength training should not only be a fixed number of repetitions corresponding to the relative load intensity. In order to ensure the relevance and effectiveness of the load arrangement, it is recommended that the load be regulated according to the size of the VL in each set of training. Not only can the target training intensity be achieved, but also the level of fatigue can be monitored in real time to prevent overfatigue, thus achieving the best training effect (Sánchez-Medina and González-Badillo, 2011; Schilling et al., 2008).

Consequently, the percentage of VL can be employed as a load modifying variable in strength training for the purpose of inducing PAP. Existing studies have demonstrated that 20% VL represents a critical value below which explosive power is favoured, and above which it is more favourable for musCIe hypertrophy (Pareja-Blanco et al., 2020). Nevertheless, studies have also indicated that 10% VL is more favourable for explosive power gains than 20% VL. A study found that while both 10% and 20% VL programs led to similar strength gains, the 10% VL condition provided better outcomes in explosive power due to reduced fatigue levels (Krzysztofik et al., 2022). Research has shown that lower VL thresholds, such as 10% VL, may be more effective for maximizing explosive power gains compared to higher thresholds like 20% VL. This is because less fatigue is accumulated with lower VL, allowing for better power output during subsequent efforts (Andersen et al., 2024).

However, there is still a lack of extensive research applying these methods specifically to boxing programs, and more studies are needed to establish the superiority (or lack thereof) of VL-induced PAP compared to traditional PAP methods (González-Badillo et al., 2022). Therefore, the present study investigated the effects of PAP on punching ability in boxers based on different VLs.

1.1 Aim and objectives

In this study, three different PAP training protocols with different loads were designed and tested on the boxers' punching ability sub-indicators at different recovery times to compare and analyse the effects of three different PAP training protocols, namely, 10%VL and 20%VL, and the traditional protocol (based on repetitions of 1%1RM), on punch force, speed and power, so as to investigate the optimal VL threshold and recovery time.

The present study expects to optimise athletic performance and promote punching ability in boxers by exploring an intervention protocol focusing on load scheduling refinement and individualisation. It also promotes the further application of the activation modality of the PAP in practice, provides data support and theoretical basis for the training load arrangement of the boxers' pre-fight warm-up programme and the PAP in their daily training, and provides data support and theoretical basis for in-depth research in this field.

2 Materials and methods

2.1 Sample and participants

Twenty-four male elite boxers (age: 19.14 ± 1.82; height: 174.52 ± 3.76 cm; body weight: 64.75 ± 6.57 kg; 1RM squat: 118.62 ± 11.66 kg; sport level: national) consented to participate in this study. Participants reported no history of knee injury within 6 months prior to the testing. They were informed about the procedure and the aim of the study, and subsequently they provided their written consent for participation. Ethical consent was provided by Shanghai University of Sport research ethics committee (approval number: 102772023RT153) and in accordance with the Helsinki deCIaration.

2.2 The main experimental steps

2.2.1 Experimental equipment

In this study, the athlete's punching ability was measured by StrikeTec (Striketec Sensor Kit, StrikeTec, TX, United States). It integrates inertial measurement unit (IMU) technology, using accelerometers and gyroscopes to capture real-time data on punch force, speed and power. The sensors are installed in boxing gloves, and the collected data is transmitted via Bluetooth to a mobile app for analysis and visualization (Menzel and Potthast, 2021a; Menzel and Potthast, 2021b).

Velocity loss was derived by GYM (GymAware Power Tool, Kinetic Performance Technologies, Australia), recording the velocity of barbell movement during the squat. It operates by utilizing a linear position transducer to measure bar velocity during resistance training exercises. The device is attached to the barbell or weight, and as the athlete performs lifts, it captures real-time data on movement velocity production. This data is transmitted to a mobile app, where it is analyzed and visualized (Dorrell et al., 2019; Orange et al., 2020).

2.2.2 Experimental methods

2.2.2.1 Velocity loss test

The lower limb muscle fatigue was monitored in real time by monitoring the velocity of barbell movement during exercise with the GYM. In this study, the 10VL, 20VL, and CON all used 85% 1RM as the loading intensity (Garbisu-Hualde and Santos-Concejero, 2021), and in the selection of loading volume, the 10VL and 20VL monitored the loading through the real-time feedback from the GYM, and determined the loading volume (the number of repetitions) based on the velocity loss in the feedback data, and the CON used 6-8 repetitions as the loading volume.

The GYM was prepared and placed on the side of the squat rack prior to the start of the test, and the subject's body weight and 85% of the 1RM weight were entered into the data terminal. The sensing

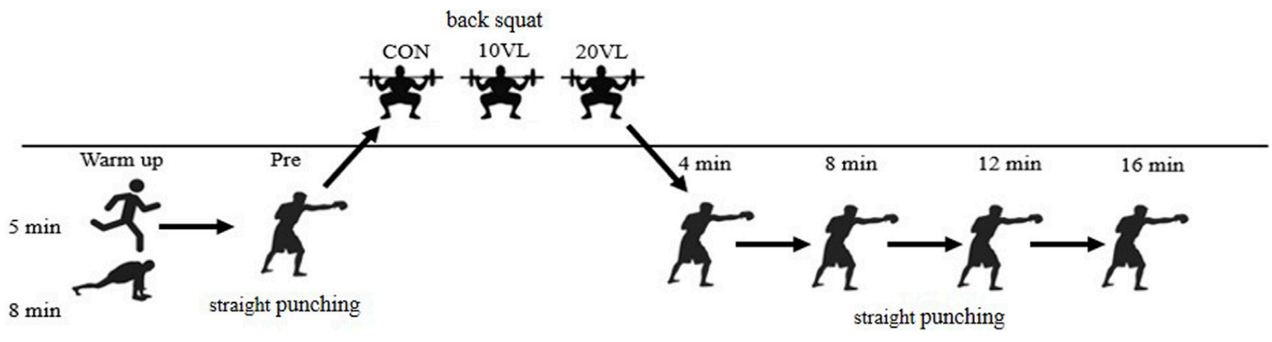

FIGURE 1
Flowchart of the experiment.

cable of the GYM was then connected to the barbell end and manually zeroed in the data terminal. The test required the subject to perform three squats at 85% of the 1RM load intensity, squatting until the knee was bent at slightly more than 90°, or until the thighs were parallel to the floor, pausing for one second, and then squatting quickly to the starting position. The maximum value of the average squat velocity over the three sessions was recorded as the average squat velocity during formal training using real-time feedback data from the GYM. During the formal training intervention, if the subject's velocity per squat was 90%–100% (10VL) and 80%–100% (20VL) of the measured mean velocity, training continued, and when the mean velocity per squat was lower than 90% (10VL) and 80% (20 VL) of the measured mean velocity, i.e., the velocity loss was more than 10% (10VL) and 20% (20VL), the training was ended.

2.2.2.2 Punching ability test

Subjects were required to wear uniform boxing gloves. Before the start of the test, the chip in the StrikeTec device was placed on the outside of the subject's wrist joint and secured with a strap. The data terminal was zeroed, the subject's height, weight, and age were entered, and the subject was explained the requirements of the test maneuvers. The punch requires the subject to freely control the distance between the sandbag and the subject, and under the condition of full stomping and force generation, the subject can take a step up to punch the sandbag with full force. The interval between single punch was 15 s. After completing 5 punches and generating valid data, the maximum and minimum values in the data were excluded, and the average value of the remaining 3 punches was taken as the final result. The average punch power data comes from the product of average punch speed and average punch force. During the testing process, the staff should monitor the quality of the subject's punches to prevent ineffective punches. If there is an error in the action need to be re-punch after an interval of 15 s, until the end of the test.

2.2.3 Eexperimental procedure

The experimental procedure is shown in Figure 1. The subjects were randomly assigned to three groups: CON, 10VL, and 20VL. The 85% 1RM squat was selected as the activation movement. At the beginning of the experiment, subjects were asked to perform a 5-min jogging warm-up as well as dynamic stretching, followed by an 8-min boxing-specific warm-up, after which the pre-test began.

2.2.3.1 CON

The CON performed a punching ability pre-test after completing the warm-up, with a 5 min interval before completing a pre-warm-up of 85% 1RM x 3 reps of squats, and then began the formal workout 4 min later by completing 85% 1RM x (6–8) reps of squats. The formal workout entailed completing two sets with a 2-min interval between sets. Striking ability tests were performed at four time points, 4, 8, 12, and 16 min after completion of the formal training, and the results of the subjects' punch force, punch speed, and punch power data were recorded.

2.2.3.2 10VL

The 10VL underwent a pre-test of punching ability after completing the warm-up, and after a 5-min interval, completed a pre-warm-up of 85% of 1RM x 3 repetitions of squats, while the highest average velocity during the three squats was recorded using the GYM. Formal training began 4 min later, and subjects were required to complete 85% of 1RM squats, with the number of repetitions, i.e., the amount of load, based on the number of repetitions, i.e., the load, was based on the loss of velocity as measured by the GYM, and the training was completed when the loss of velocity exceeded the 10% threshold. Formal training required the completion of two sets with a 2-min interval between sets. The punching ability test was conducted at the 4th, 8th, 12th, and 16th minutes after the completion of the formal training, and the results of the subjects' punch force, punch speed, and punch power data were recorded.

2.2.3.3 20VL

The 20VL underwent a pre-test of punching ability after completing the warm-up, and after a 5-min interval, completed a pre-warm-up of 85% of 1RM x 3 repetitions of squats, while the highest average velocity during the three squats was recorded using the GYM. Formal training began 4 min later, and subjects were required to complete 85% of 1RM squats, with the number of repetitions, i.e., the amount of load, based on the number of repetitions, i.e., the load, was based on the loss of velocity as measured by the GYM, and the training session ended when the loss of velocity exceeded the 20% threshold. Formal training required the completion of two sets with a 2-min interval between sets. The punching ability test was conducted at the 4th, 8th, 12th, and 16th minutes after the completion of the formal training, and the results of the subjects' punch force, punch speed, and punch power data were recorded.

2.2.4 Outcome measures

Squat maximum strength: 1RM squat (SQ), Velocity loss (VL, velocity is the rate of change of an object's position, including direction and magnitude): barbell movement velocity during squat. Punching ability: punch force (PF, force is an interaction that changes the motion of an object when unopposed), punch speed (PS, speed is how fast an object is moving, measured as distance traveled per unit time), and punch power (PP, power is the rate at which work is done or energy is transferred) on dominant and non-dominant sides (Smith et al., 2000).

2.3 Statistical analysis

Descriptive statistics (means and standard deviations) were performed to summarize all data. Two-way analysis of variance (ANOVA) were conducted (time*group), with the between-group factor being the effect of grouping (CON, 10VL, 20VL) and the within-group factor being the measurement time (PRE, 4 min, 8 min, 12 min, 16 min). The data in each group exhibited a normal distribution, as indicated by the Shapiro-Wilk (S-W) test. The data were tested for sphericity using repeated measures ANOVA. If $p > 0.05$, spherical symmetry was met. Conversely, if $p < 0.05$, the results of the multivariate test prevailed. When there was an interaction effect between two factors, a simple effects analysis was performed for each factor. The strength of association within groups was evaluated by calculating the partial eta square (η^2) separate effect size. The larger the η^2 value, the larger the magnitude of the difference. Finally, the optimal VL and recovery time points for the PAP of boxers' punching ability were determined following multiple comparisons to analyse the between-group differences under the same load, as well as to compare the various time periods under that load with the immediate aftermath of the exercise (with the significance level taken as $p < 0.05$). All statistical analyses were performed using PRISM (GraphPad Software, Inc. Version prism 8.0 for Windows) and SPSS 26.0 software (SPSS Inc., Chicago, IL, United States).

Utilizing G*Power 3.1 software, we took a moderate effect size ($\eta^2 = 0.059$), with a statistical power of 0.8 and a significance level of 0.05. Derived the need for a minimum of 24 subjects.

3 Results

3.1 Effect of different velocity loss thresholds on punching speed

Punching speed refers to the velocity at which a punch is delivered, typically measured in meters per second (m/s). It reflects the ability of the boxer to execute punches rapidly, which is crucial for both offensive and defensive maneuvers in boxing (Horan and Kavanagh, 2012).

Table 1 shows the results of punching speed, Figure 2 shows the variation of punching speed on the dominant side at different time points.

ANOVA results showed that a significant group*time interaction could be observed on the dominant side ($F = 3.659$, $p < 0.05$, $\eta^2 = 0.125$), and a significant main effect of time could be observed ($F = 11.603$, $p < 0.001$, $\eta^2 = 0.185$). 20VL: Compared to Pre, 8 min ($p < 0.05$, 95% CI: −1.629 to −0.525) and 12 min ($p < 0.05$, 95% CI: −1.793 to −0.668) increased; 8 min ($p < 0.05$, 95% CI: −13.67 to −0.21) and 12 min ($p < 0.05$, 95% CI: −1.494 to −0.391) increased compared to 4 min; 16 min decreased compared to 8 min ($p < 0.05$, 95%CI: −1.305 to −0.146) and 12 min ($p < 0.05$, 95% CI: −1.361 to −0.397).

Figure 3 shows the variation of punching speed on the non-dominant side at different time points.

A significant group*time interaction could be observed on the non-dominant side ($F = 2.885$, $p < 0.05$, $\eta^2 = 0.191$), and a significant main effect of time could be observed ($F = 3.666$, $p < 0.05$, $\eta^2 = 0.234$). 10VL: Compared to Pre, 8 min ($p < 0.05$, 95% CI: −0.991 to −0.2) and 12 min ($p < 0.05$, 95% CI: −0.923 to −0.123) increased.

3.2 Effect of different velocity loss thresholds on punching force

Punching force is the amount of force exerted upon impact with a target, often measured in Newtons (N). It is influenced by the mass of the fist and the acceleration of the punch, adhering to Newton's second law of motion (Force = Mass × Acceleration) (Olberding and Deban, 2017).

Table 2 shows the results of punching force, Figure 4 shows the variation of the dominant side's punching force at different time points.

No significant group*time interaction was observed on the dominant side ($F = 1.352$, $p > 0.05$, $\eta^2 = 0.05$), but a significant main effect of time could be observed ($F = 19.454$, $p < 0.001$, $\eta^2 = 0.276$). CON: 12 min compared to 4 min ($p < 0.05$, 95% CI: −398.92 to −17.258) and 8 min ($p < 0.05$, 95% CI: −397.88 to −57.591) increased; 16 min decreased compared to 12 min ($p < 0.05$, 95% CI: −348.13 to −28.375). 10VL: 12 min increased compared to Pre ($p < 0.05$, 95% CI: −449.74 to - 106.2), 4 min ($p < 0.05$, 95% CI: −425.02 to −43.358) and 8 min ($p < 0.05$, 95% CI: −390.77 to −50.48); 16 min decreased compared to 12 min ($p < 0.05$, 95% CI: −387.9 to −68.138). 20VL: 12 min increased compared to Pre ($p < 0.05$, 95% CI: −423.8 to −80.26) and 4 min ($p < 0.05$, 95% CI: −453.73 to −72.073); 16 min decreased compared to 12 min ($p < 0.05$, 95% CI: −529.81 to −210.05).

Figure 5 shows the change in punching force on the non-dominant side at different time points.

No significant group*time interaction was observed on the non-dominant side ($F = 1.636$, $p > 0.05$, $\eta^2 = 0.118$), but a significant main effect of time was able to be observed ($F = 30.883$, $p < 0.001$, $\eta^2 = 0.72$). CON: Compared to Pre, 8 min ($p < 0.05$, 95% CI: −315.27 to −55.129) and 12 min ($p < 0.05$, 95% CI: −346.94 to −47.614) increased. 10VL: Compared to Pre, 4 min ($p < 0.05$, 95% CI: −332.64 to 0.071), 8 min ($p < 0.05$, 95% CI: −419.36 to −159.22) and 12 min ($p < 0.05$, 95%

TABLE 1 Results of punching speed (M±SD, m/s).

	Group	PRE	4 min	8 min	12 min	16 min
Dominant	CON	8.47 ± 0.51	8.51 ± 0.5	8.63 ± 0.62	8.7 ± 0.51	8.43 ± 0.61
	10VL	8.47 ± 0.63	8.8 ± 0.59	8.76 ± 0.63	8.89 ± 0.85	8.66 ± 0.62
	20VL	8.52 ± 0.38	8.8 ± 0.36	9.59 ± 0.53	9.75 ± 0.46	8.87 ± 0.39
Non-dominant	CON	6.72 ± 0.19	6.43 ± 1.00	6.77 ± 0.29	6.64 ± 0.52	6.57 ± 0.51
	10VL	6.76 ± 0.23	6.74 ± 0.94	7.35 ± 0.52	7.28 ± 0.33	6.92 ± 0.39
	20VL	6.76 ± 0.22	6.56 ± 0.94	6.68 ± 0.59	6.76 ± 0.63	6.94 ± 0.88

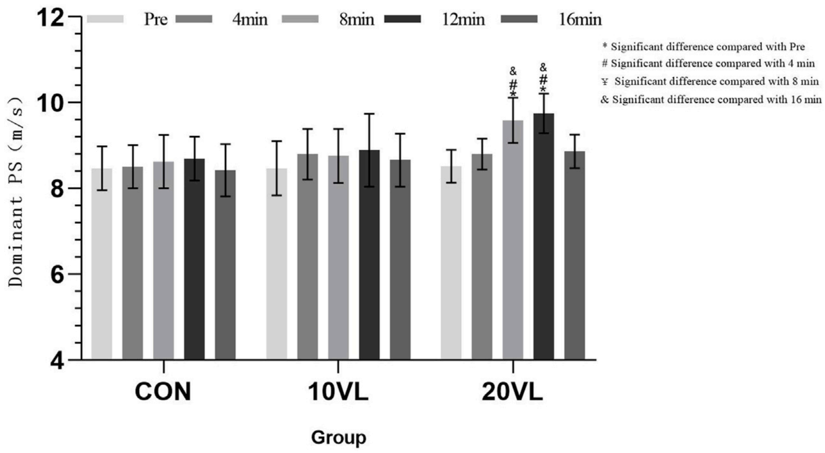

FIGURE 2
Variation in punching speed of the dominant side at different time points.

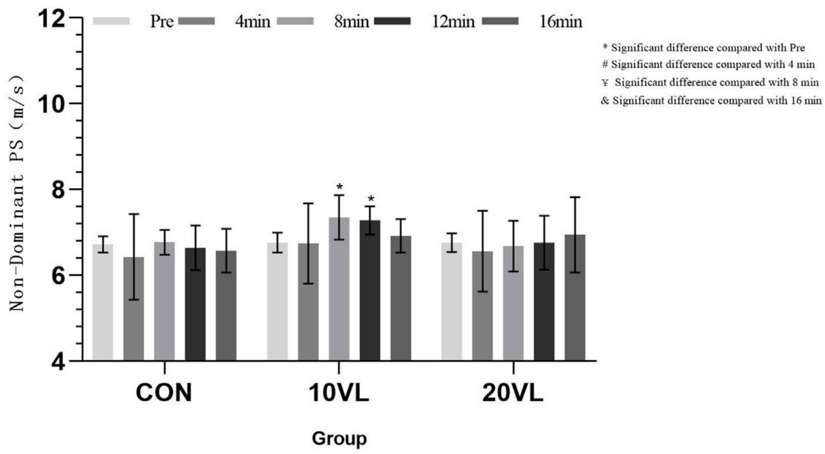

FIGURE 3
Variation in punching speed of the non-dominant side at different time points.

CI: −305.15 to −5.823) increased; 16 min decreased compared to 8 min ($p < 0.05$, 95% CI: −467.89 to −137.64). 20VL: 8 min increased compared to Pre ($p < 0.05$, 95% CI: −352.75 to −92.617) and 4 min ($p < 0.05$, 95% CI: −329.79 to −18.347); 16 min decreased compared to 8 min ($p < 0.05$, 95% CI: −439.52 to −109.26).

3.3 Effect of different velocity loss thresholds on punching power

Punching power combines both speed and force to quantify the effectiveness of a punch. It is often described as the ability to deliver a

TABLE 2 Results of punching force (M±SD, N).

	Group	PRE	4 min	8 min	12 min	16 min
Dominant	CON	2,747.71 ± 134.89	2,840.32 ± 224.41	2,820.67 ± 169.72	3,048.41 ± 156.23	2,860.15 ± 135.84
	10VL	2,765.33 ± 138.77	2,809.11 ± 252.2	2,822.67 ± 243.69	3,043.3 ± 197.11	2,815.28 ± 222.49
	20VL	2,827.36 ± 186.15	2,816.49 ± 171.34	2,910.67 ± 277.51	3,079.39 ± 178.5	2,709.46 ± 179.8
Non-dominant	CON	2,270.86 ± 113.43	2,361.86 ± 220.77	2,456.06 ± 177.01	2,468.14 ± 220.79	2,395.16 ± 197.94
	10VL	2,263.42 ± 113.37	2,429.71 ± 200.35	2,552.71 ± 159.23	2,418.91 ± 187.42	2,249.95 ± 161.7
	20VL	2,318.88 ± 80.85	2,367.5 ± 232.75	2,541.57 ± 186.33	2,426.73 ± 180.32	2,267.18 ± 181.06

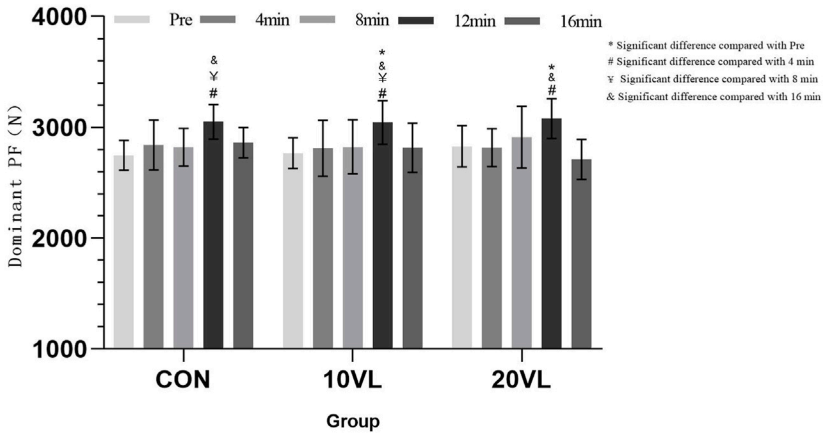

FIGURE 4
Variation in punching force of the dominant side at different time points.

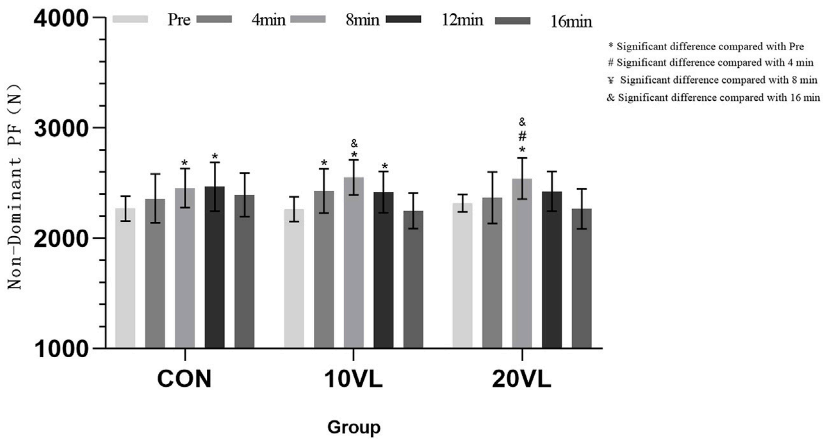

FIGURE 5
Variation in punching force of the non-dominant side at different time points.

powerful strike capable of generating significant impact energy, typically measured in Watts (W) or calculated using the formula Power = Force × Speed (Cormie et al., 2010).

Table 3 shows the results of punching power, Figure 6 shows the variation of the punching power of the dominant side at different time points.

A significant group*time interaction could be observed on the dominant side ($F = 3.251$, $p < 0.05$, $\eta^2 = 0.113$) and a significant main effect of time could be observed ($F = 28.448$, $p < 0.001$, $\eta^2 = 0.358$). CON: 12 min increased compared to Pre ($p < 0.05$, 95% CI: −5,361.98 to −1,210.09) and 4 min ($p < 0.05$, 95% CI: −4,673.86 to −128.433); 16 min decreased compared to 12 min

TABLE 3 Results of punching power (M±SD, W).

	Group	Pre	4 min	8 min	12 min	16 min
Dominant	CON	23,274.03 ± 1980.7	24,158.92 ± 2,357.08	24,273.88 ± 1,431.94	26,560.06 ± 2,353.01	24,127.27 ± 2,316.2
	10VL	23,388.04 ± 1707.93	24,665.3 ± 2062.62	24,757.17 ± 3,121.62	27,027.17 ± 2,903.33	24,401.17 ± 2,701.06
	20VL	24,073.61 ± 1857.87	24,818.83 ± 2077.41	27,959.35 ± 3,403.33	30,033.75 ± 2,546.94	23,994.94 ± 1,434.54
Non-dominant	CON	15,253.66 ± 801	15,218.72 ± 2,840.98	16,621.81 ± 1,479.4	16,366.68 ± 1725.37	15,726.5 ± 1717.08
	10VL	15,300.22 ± 987.12	16,335.81 ± 2,396.31	18,751.11 ± 1,469.64	17,641.08 ± 1852.45	15,549.81 ± 1,215.71
	20VL	15,664.97 ± 701.42	15,494.14 ± 2,490.46	16,994 ± 1977.05	16,433.52 ± 2,309.82	15,678.82 ± 2064.1

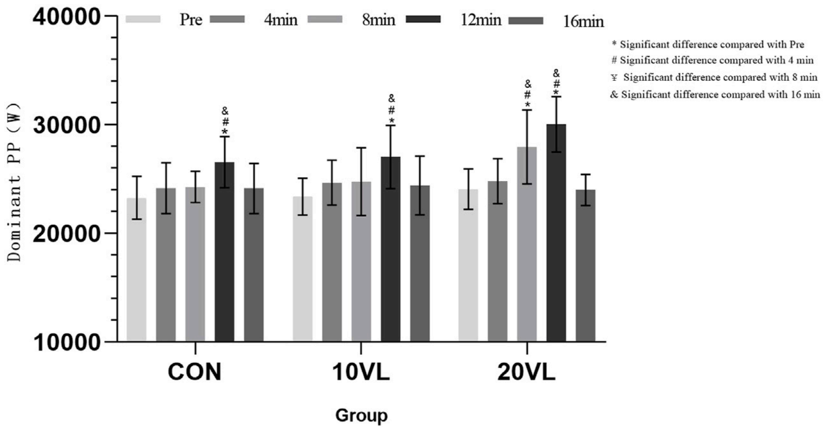

FIGURE 6
Variation in punching power of the dominant side at different time points.

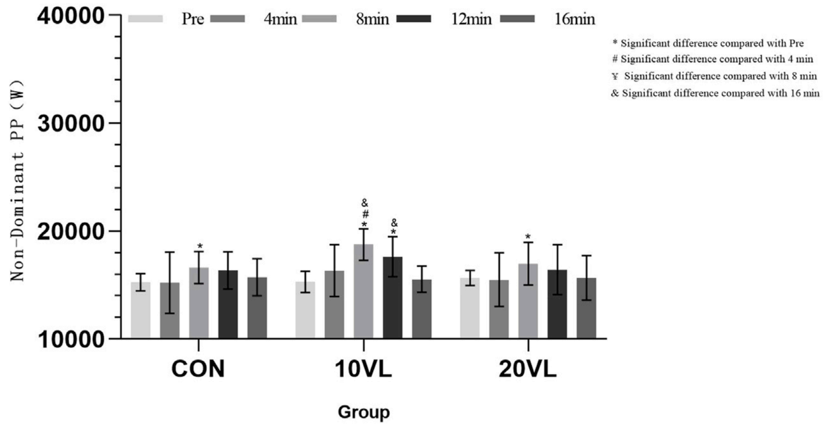

FIGURE 7
variation of punching power on the non-dominant side at different time points.

($p < 0.05$, 95% CI: −4,573.44 to −292.143). 10VL: 12 min increased compared to Pre ($p < 0.05$, 95% CI: −5,715.08 to −1,563.19) and 4 min ($p < 0.05$, 95% CI: −4,634.59 to −89.162); 16 min decreased compared to 12 min ($p < 0.05$, 95% CI: −4,766.65 to −485.353). 20VL: Compared to Pre, 8 min ($p < 0.05$, 95% CI: −6,397.39 to −1,374.09) and 12 min ($p < 0.05$, 95% CI: −8,036.09 to −3,884.2) increased; compared to 4 min, 8 min ($p < 0.05$, 95% CI: −5,682.62 to −598.418) and 12 min ($p < 0.05$, 95% CI: −7,487.64 to −2,942.21) increased; 16 min decreased compared to 8 min ($p < 0.05$, 95% CI: −6,629.4 to −1,299.43) and 12 min ($p < 0.05$, 95% CI: −8,179.47 to −3,898.17).

Figure 7 shows the variation of punching power on the non-dominant side at different time points.

The non-dominant side was able to observe a significant group*time interaction (F = 2.483, p < 0.05, η^2 = 0.169) and was able to observe a significant main effect of time (F = 24.782, p < 0.001, η^2 = 0.674). CON: 8 min increased compared to Pre (p < 0.05, 95% CI: −2,628.91 to −107.386). 10VL: Compared to Pre, 8 min (p < 0.05, 95% CI: −4,711.65 to −2,190.13) and 12 min (p < 0.05, 95% CI: −3,828.52 to −853.199) increased; 8 min increased compared to 4 min (p < 0.05, 95% CI: −4,380.14 to −450.447); 16 min decreased compared to 8 min (p < 0.05, 95% CI: −4,906.01 to −1,496.58) and 12 min (p < 0.05, 95% CI: −3,683.3 to −499.243). 20VL: 8 min increased compared to Pre (p < 0.05, 95% CI: −2,589.79 to −68.272).

4 Discussion

This study represents the inaugural investigation into the impact of PAP induced by varying VL on the punching ability of boxers. The study employed a three-pronged approach, encompassing the examination of the load stimulus, fatigue effect and fatigue recovery time at distinct VL. The objective was to identify the optimal PAP, as well as the VL and time points that would induce this effect.

4.1 Post-activation enhancement effect on punching ability at different velocity loss thresholds

Current research in this area suggests that 10VL and 20VL may be better for athletes who need explosive power, but it is not known which is more appropriate for boxers (Pérez-Castilla et al., 2018).

We found that the 10VL and the 20VL exhibited significantly enhanced punching ability compared to the CON. However, the magnitude of change in various sub-indicators of punching ability at different VL varied. Furthermore, the study revealed a significant asymmetry between the punching abilities of the dominant and non-dominant sides. The punching ability of the dominant side was found to be significantly superior to that of the non-dominant side at different VL. This is attributed to the fact that boxing techniques encompass forehands and backhands, and that long-term training tends to result in uneven musCIe strength on both sides of the body. Boxers tend to utilise the dominant side with greater frequency in order to land as many effective punches as possible. Although the data indicates that the punching ability of the dominant side is significantly superior to that of the non-dominant side, which appears to be more conducive to effective punching, it is important to recognise the value of training the non-dominant side. This is due to the complexity of boxing technical movements, the uncertainty of the use of technical and tactical skills, and the transition between attack and defence in the ring.

We therefore discuss the differences between the dominant and non-dominant sides at different VLs separately and explore the reasons for the differences.

The present study demonstrated that the PAP induced by 20VL was beneficial in increasing the punching speed of the dominant side of the subjects. Compared with the CON and the 10VL, the 20VL exhibited the most favourable outcomes, likely due to the load effectively improving the neuromuscular coordination of the subjects' organisms and facilitating greater fast musCIe fibre recruitment (Pareja-Blanco et al., 2017b; Sañudo et al., 2020). The dynamics of the kinetic chain necessitate that a straight punch requires the lower extremity to generate force from the stirrups, which is then transferred from the core to the arm to complete the end release of the force. Consequently, the amount of force generated by the lower limb stirrups will have a direct impact on the rate of growth of the force, and thus on the speed of the punch at the time of release of the upper limb. The 20% VL can enhance the neural control of musCIes in the lower limb stirrups (Enoka, 2012; Heckman and Enoka, 2012), which is conducive to the improvement of punching speed. Furthermore, the velocity of power transmission within the kinetic chain is also influenced by the excitation and inhibition of the motor nerve centre within the cerebral cortex and the coordination between the upper and lower limbs. Existing studies have confirmed that the PAP induced at the threshold of 20% loss of velocity can optimise the effect of these factors (González-Badillo et al., 2011).

The PAP induced by the 20VL in the present study was able to increase the punching force of the subjects. This is likely due to the fact that the activation training at this load effectively increased the sensitivity of calcium ions in the myocytes, which led to the enhancement of the fast musCIe contraction. At the same time, by changing the pinnation angle, the musCIe contraction force was enhanced (Zimmermann et al., 2020). The recruitment of more fast musCIe fibres was facilitated by 20% VL, as the preliminary activation training increased neural excitability and accelerated the conduction rate of action potentials in the nerves. This enabled the body to recruit more fast motor units (Pareja-Blanco et al., 2017a), which ultimately manifested itself in the enhancement of the subject's punching force. This hypothesis has been corroborated by previous studies, inCIuding those conducted by Galiano et al. who conCIuded that 20% VL was efficacious in augmenting maximal strength and lower limb explosive power (Galiano et al., 2022), and Folland and Santanielo et al. who demonstrated that 20% VL was beneficial in promoting changes in the pinnation angle of the musCIe fibres, thereby increasing the force of the musCIe contraction (Folland and Williams, 2007; Santanielo et al., 2020).

Given that punch power is positively correlated with punch force and punch speed, the results of the study demonstrated consistency between the variables of PP and PS and PF. The maximum values were observed on the dominant side at 12 min in the 20VL and on the non-dominant side at 8 min in the 10VL.

4.2 Post-activation enhancement effects at different velocity loss thresholds at different time points

Most of the studies suggested that the PAP occurs at 4 min post-intervention, and the following 8 min, 12 min and 16 min were used as the observation points (Gilbert and Lees, 2005), but in practice we found that the time point at which the optimal PAP occurs varies between VLs.

The PAP undergoes changes at different time points due to the generation and dissipation of fatigue. Following activation training, the PAP is induced while fatigue ensues due to the stimulation of the body by the load, and there is a dynamic equilibrium between the PAP and the fatigue effect. In this study, the peak is the point in time when the fatigue effect is minimal and the PAP is optimal. In rugby, which also requires lower body explosive power, the researchers observed that the level of lower body explosive power increased significantly at 8 and 12 min post-intervention. This indicated that the PAP was more pronounced at 8–12 min intervals (Kilduff et al., 2007). These findings are consistent with those of the present study, which demonstrated that the bilateral punching ability of the groups exhibited a significant enhancement at both time nodes. The dominant side, 20VL, exhibited the most pronounced PAP at 12 min, while the non-dominant side, 10VL, demonstrated the optimal PAP at 8 min.

The duration of fatigue recovery is directly proportional to the intensity of the load stimulus to which the organism is exposed. Consequently, the interval time between activation training and testing exerts a significant influence on the acute enhancement effect of the PAP on the organism. If the interval time is too short, the organism is in a state of fatigue, and the fatigue effect is greater than the PAP, which is not conducive to the enhancement of athletic performance. Conversely, if the interval time is too long, the fatigue effect is gradually decreasing, but the PAP will also subside. This is why the results of the present study show a rising-deCIining wave pattern at each time point.

In terms of punching speed on the dominant side, the 20VL demonstrated a significant increase at 8 min and reached a peak at 12 min. This suggests that the activation effect emerged gradually after the intervention, as fatigue recovered, and produced an optimal PAP at 12 min. A sharp deCIine was observed at 16 min, and the other two groups also showed a similar downward trend. The CON demonstrated a lower result than the pre-test at 16 min, indicating that the PAP induced by activation training gradually disappeared at this time. The non-dominant side exhibited a wave-like deCIine-rise-deCIine trend, which was attributed to the unequal musCIe strength between the non-dominant and dominant sides. The non-dominant side was found to be weaker and more prone to fatigue, while the dominant side was able to withstand greater loads and was less fatigued. Consequently, the fatigue effect of the organism exceeded the PAP at 4 min, resulting in a lower test result than the pre-test.

A comparable waviness was observed in the punching force, with the dominant side reaching its peak at 12 min in all three groups and exhibiting less fluctuation on the non-dominant side. However, no significant difference was found in the individual measurement time nodes. In terms of punching power, the 20VL on the dominant side demonstrated a notable increase in both the 8-min and 12-min time nodes. The 10VL on the non-dominant side exhibited a similar pattern, with a sharp increase and peak at 8 min. In addition to the differences in fatigue effect and fatigue recovery time under different VL, it is also essential to consider the changes in the physical function of the subjects under the fatigue state. When the speed and force of the punch remain unchanged, the coordination and stability of the body are negatively affected, which in turn impairs the kinetic chain's conduction effect. This results in a reduction in punching power. The rationale behind the present study's decision to increase the punching power test indexes is to address this issue.

The differing groups and time points for the optimal PAP between the dominant and non-dominant sides in this study were attributed to the uneven musCIe strength between the two sides of the subjects, which was a consequence of the characteristics of the boxing programme. This inconsistency in the stimulation of the training loads received by the musCIes on the dominant and non-dominant sides led to differences in the fatigue effect, as well as in the time point at which the fatigue effect appeared and disappeared. This renders it impossible to achieve the optimal PAP under the same training load bilaterally.

5 Limitation

The subjects in this study were all male. Further research is needed to determine whether the conCIusions drawn are also applicable to female boxers. This study only investigated the effects of PAP on the punching ability of boxers at different velocity loss thresholds from the perspective of athletic performance. It did not address the physiological mechanisms.

6 Conclusion

We found that activation training based on velocity loss induced a significantly better PAP than traditional activation training with fixed loads, which was more effective in improving boxers' punching ability in a short period of time. The percentage of VL can be employed as a load modifying variable in strength training for the purpose of inducing PAP, which helps to improve the relevance and effectiveness of activation training through individualised, real-time monitored data feedback, applicable to the competition demands of high-level athletes.

Due to the interplay of load stimulus, fatigue effect and fatigue effect recovery time, we found that the PAP produced by different VL at different recovery time nodes differed and showed wave-like changes. We also found that there was a significant asymmetry between the punching ability of the dominant and non-dominant sides, with the punching ability of the dominant side being significantly better than that of the non-dominant side at different VL, and that the VL and time nodes at which the optimal PAP could be produced were not the same for both sides. The optimal effect was observed for the dominant side at the 12th minute of the 20% VL, while for the non-dominant side, the optimal effect was observed at the 8th minute of the 10% VL.

In practice, given that the dominant side has a greater punching ability and frequency of use than the non-dominant side in boxing events, it is recommended that a 20% VL be selected for activation and a 12-min interval in the pre-fight warm-up to achieve the best activation effect of the dominant side in order to maximise the short-term training benefit. In daily training, it is recommended to balance the dominant and non-dominant sides, but the results of the present study are only for the pre-competition warm-up, and its long-term training effect has not been confirmed, so further research is expected in the future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Shanghai University of Sport Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

WC: Conceptualization, Methodology, Writing–original draft, Writing–review and editing. YC: Data curation, Investigation, Software, Validation, Writing–review and editing. DW: Funding acquisition, Resources, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Is inertial training more effective than traditional resistance training in young healthy males?

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Objectives: Inertial training, also called flywheel training is more and more popular among sportsmen. The available data concerning the effectiveness of inertial training compared to conventional resistance strength training are contradictory. The aim of this study was to compare the impact of inertial training (IT) vs. traditional gravity-dependent resistance training (TRT) on elbow flexor and knee extensor strength.

Methods: Twenty-six young, recreationally active males were randomized into IT group (n = 13) or TRT group (n = 13). Both groups performed strength training three times a week for 6 weeks. Before and after training, the maximum force of the trained muscles was evaluated under training conditions (one repetition maximum under gravity-dependent conditions and maximal force under inertial conditions) and isometric conditions. Countermovement jump, squat jump, pull-up test, and limb circumference were also evaluated.

Results: Elbow flexor muscle strength and arm circumference increased significantly in both IT and TRT over the course of training. There were no significant differences in relative muscle strength increases between groups. Knee extensor muscle strength also improved significantly in IT, regardless of the tested conditions, while TRT showed significant changes in one repetition maximum and isometric force but no significant changes in force obtained under inertial conditions. Thigh circumference increased in IT ($P \leq 0.05$) but was unchanged in TRT. Jumping abilities improved significantly in both groups, without any differences between groups.

Conclusion: We cannot confirm the superiority of inertial training over traditional resistance training definitively. Nevertheless, inertial training had a slight advantage over traditional resistance training when knee extensor muscle training was considered.

KEYWORDS

inertial, resistance, trainings comparison, muscle strength, elbow flexors, knee extensors

1 Introduction

Inertial training is a strength training method that is performed using a specialized gravity-independent device. Studies on the effectiveness of inertial training in young, untrained healthy participants have demonstrated that it is a safe and highly effective training method (Seynnes et al., 2007; Naczk et al., 2016a). Moreover, there are progressively more studies showing that inertial training is an effective strength training method for well-trained professional athletes (Askling et al., 2003; Maroto-Izquierdo et al., 2017a; Naczk et al., 2017). Moreover, inertial exercises are often used for effective rehabilitation in different diseases (Fernandez-Gonzalo et al., 2016; Harris-Love et al., 2021; Naczk et al., 2022) or to improve the quality of life of people with deteriorating locomotor system efficiency (e.g., the elderly) (Brzenczek-Owczarzak et al., 2013; Kowalchuk and Butcher, 2019; Naczk et al., 2020). During inertial training, great muscle tension is maintained during both concentric and eccentric contractions. During traditional resistance training EMG amplitude is markedly lower during eccentric than concentric actions given the same force or load is employed. However, muscle fiber activation during the eccentric action performed with inertial exercise is greater than noted during traditional resistance training (Norrbrand et al., 2008).

Moreover, muscle activity (assessed by EMG amplitude) in inertial exercises is even greater during eccentric contraction than during concentric contraction (Norrbrand et al., 2008). Due to the significant muscle strength increases that develop over relatively short periods of time, the effectiveness of inertial training can be greater than that of traditional resistance training. There is considerable discussion about the superiority of inertial training (also called flywheel training) over traditional resistance strength training. In a summary of their review article, Maroto-Izquierdo et al. (2017b) stated that inertial training appeared to be more effective than traditional resistance exercise in promoting increases in capacities strongly associated with athletic performance. Shortly after publication of that paper, Vicens-Bordas et al. (2018a) in a letter to the editor responded that they believed the methodological shortcomings in the Maroto-Izquierdo et al. (2017b) called its conclusion into question—that inertial flywheel resistance training is superior to traditional weight stack exercises for promoting skeletal muscle adaptations in terms of strength, power, and size in healthy participants and athletes. Maroto-Izquierdo et al. (2018) responded in that letter to the editor that their methodology was satisfactory and their conclusions were justified. Subsequently, Vicens-Bordas et al. (2018b) of this issue; they stated in their conclusions that inertial flywheel resistance training was not superior to gravity-dependent resistance training in improving muscle strength. However, since all cited authors drew their conclusions based on reviews, there is no objective data comparing the effectiveness of inertial training vs. traditional weight training. Some authors have tried to compare the effectiveness of inertial training vs. traditional weight training, but the movement techniques in the two training groups were different and/or the estimations of training loads were not homogeneous (de Hoyo et al., 2015; Greenwood et al., 2007; Onambélé et al., 2008). We assert that the lack of data from a precise, objective, and reliable comparison of the effectiveness of inertial training vs. conventional strength training is probably due to methodological limitations. In gravity-dependent strength training, the training load is determined by the relative value of 1RM, whereas it is not possible to determine the value of 1RM in inertial training. The level of maximum force achieved during inertial exercise depends on both the load used and the speed of movement. Our experiences with inertial training indicate that depending on the individual characteristics of the participant, maximum force is obtained at different values of the applied load and speed of movement. We surmise that this problem has prevented researchers from making a direct, objective comparison between the effectiveness of inertial training and gravity-dependent strength training. To make such a comparison, a novel methodology needs to be developed to determine the load in inertial training, which would be very similar to the load used in traditional weight training. Naczk et al. (2016b) proposed an interesting idea for determining the load in inertial training. They claimed that it is appropriate to use a different load for each participant to reach during inertial exercises but the same maximum speed of movement by all participants. In our opinion, this idea can be modified to create a comparable methodology for studying the differences between inertial training and conventional strength training.

The data concerning the effectiveness of inertial training vs. conventional strength training are contradictory. The aim of this study was to directly compare the effectiveness of inertial training and conventional strength training in young healthy males. It can be assumed that both trainings will be effective in increasing muscle strength and power tested in various conditions. It is possible that due to its specificity, inertial training may be more effective than traditional strength training.

2 Materials and methods

2.1 Study participants

Forty-two young males attended an initial recruitment meeting, and 30 agreed to participate in the study. Only volunteers who met the following inclusion criteria could participate in the study: in generally good health, at least 150 min of moderate physical activity per week for at least the last year, lack of professional training, and with a valid COVID-19 vaccination certificate. The exclusion criteria were: tendon or ligament injury in the previous 2 months and fractures in the previous 3 months. After applying these criteria, the study ultimately included 26 men (mean ± standard deviation: age 20.4 ± 1.18 years; body mass 81.0 ± 11.4 kg; height 184 ± 6.28 cm). The participants were physical education students, none of the participants was a competitive athlete. The participants were randomly allocated into two groups: inertial training group (IT, n = 13) or traditional gravity-dependent resistance training (TRT, n = 13) using the chit method, which is a simple method of generating random sequences. Both groups participated in 6 weeks of training, with IT performing inertial training and TRT performing traditional gravity-dependent resistance training. All participants were asked to maintain their standard diet and physical activity levels throughout the duration of the study. However, we did not control their lifestyle. All subjects provided written informed consent to participate in the study. Moreover, the participants showed in Figure 1, provided

FIGURE 1
Participant positions during inertial training and testing; **(A)** elbow flexion, **(B)** knee extension.

written informed consent for their images to be published. All procedures were approved by the local ethics committee (KB-UZ/34/2021), with approval based on the Declaration of Helsinki, and all methods were carried out in accordance with relevant guidelines and regulations. The participants and the public were not involved in the design, or conduct, or reporting, or dissemination plans of the research.

2.2 Estimation of training loads

To compare the effectiveness of the two types of training, we decided to use a novel method of determining loads in inertial training to make the training load in both training groups as similar as possible. Before training, participants learned exercise techniques in resistance and inertial conditions during two familiarization sessions. Then, 1RM was determined for unilateral elbow flexion and for unilateral leg extension (the exercises technique was the same as described in the training section). Next, the participants performed one set of unilateral flexion in the elbow joint (12 repetitions) and one set of unilateral extension in the knee joint with a load of 70% 1RM. During each set, the performance time was measured - the participants were encouraged to complete the set in the shortest time possible. Two days later, the training load for inertial training was determined using a Cyklotren inertial device (Inerion, Stanowice, Poland) according to Naczk et al. (2016b) recommendations. Each participant performed several sets of exercises with different loads. The load was increased or decreased so that the time to perform 12 repetitions (as fast as possible) was the same (with an accuracy of 0.5 s) as in the set time with 70% 1RM using traditional weights. If it was not possible to determine the load for inertial exercises using three sets with 5-minute breaks in between, the test was repeated the following day. The range of motion and body position of the participants during load determination were identical to those under resistance conditions.

2.3 Methodology limitation

We are aware that described above estimation of training loads and training protocols has some limitations. It should be clearly stated that in inertial training setting of training load, e.g., 70% of 1RM as in traditional weight training is not possible. In inertial training, the muscle load depends on both the speed of movement and the applied load. However, it should be noted that in inertial training using relatively light loads and high speed of movement, the muscle load (and fatigue) and post-training muscle strength increase may be equal or even greater compared to use larger loads and slower speed of movement (Naczk et al., 2014). We attempted to create a similar training protocol for both types of training. However, we recognize that these training protocols may have different effects on the body. In resistance training, failure fatigue appears at the end of the set, in inertial training after the first 3 repetitions - in each subsequent repetition the subject is able to accelerate the flywheel but develops less and less strength. However, in our opinion, the methodology of both trainings was as similar as possible. However, we have not found any attempt to directly compare the effectiveness of both types of training in the literature, so the methodology described above is original and may contain some flaws.

2.3.1 Training

Both groups performed their training three times a week (Monday, Wednesday, and Friday) between 7:00 a.m. and 8:30 a.m. for 6 weeks. TRT performed traditional gravity-dependent resistance training using a weighted leg extension bench, while IT performed inertial training using the Cyklotren inertial device. Training was supervised by the same three researchers. Before each training session, standardized warm-ups were performed, either 5 min of submaximal cycling using upper and lower body ergometers with eight repetitions at 50% 1RM (TRT), or eight slow cycles with the Cyklotren device (IT). Each session trained two muscle groups: elbow flexors and knee extensors. Each exercise included three sets, with the right and left extremities being exercised separately. Twelve repetitions were performed in each set, and there was a 2-minute break between consecutive sets. A single training session lasted 20–25 min. Each exercise for the elbow flexors was performed in a standing position. In the starting position, the active arm was fully extended at the elbow joint. During inertial training of the elbow flexors, the participant held the handle connected to the rope, which was fully extended and tensed, with their hand in supination. To begin the exercise, the subject flexed his elbow. Each exercise for the knee extensors was performed in a seated position on a bench. In the starting position, the active leg was flexed at the knee joint to approximately 90°. To begin the exercise, TRT subjects straightened their knee moving the bench handle, while IT participant straightened their knee pulling the rope attached to the ankle. The range of motion was the same for both types of training: approximately 130° for the elbow flexors and approximately 80° for the knee extensors. Training loads were constance in both groups. We realize that the lack of load progression throughout the training was a limitation, however re-assessing training loads was troublesome. Even though the procedure of estimating 1RM is quick and easy, estimating the training load in IT would have been fatiguing (it sometimes took 2 days - see "Estimation of training loads"), which could have had a negative impact on the training process.

2.4 Measurements

Muscle strength was tested under different conditions before and after training. In addition, jumping ability, body composition, and limb circumference were evaluated. Measurements were taken on five separate days.

2.4.1 1RM

1RM was determined for unilateral elbow flexion in a standing position using dumbbells and for unilateral leg extension in a seated position. The 1RM value was determined using traditional weights, according to National Strength and Conditioning Association (2008) guidelines. The participants performed a light warm-up set with 5–10 repetitions at 50% of estimated 1RM, followed by 2–3 heavier warm-up sets of 2–5 repetitions with loads increasing by 10%–20% at each set. Participants then began completing trials of 1 repetition with increasing loads (10%–20%) until they were no longer able to complete a single repetition. The highest load (kg) successfully lifted through the entire range of motion with the right arm with proper technique was denoted as the 1RM. Two min of rest were used between successive warm-up sets and 1RM trials.

2.4.2 Measurement of maximal force under inertial conditions

The maximal force under inertial conditions (IFmax) was measured using the Cyklotren device (Naczk et al., 2015). The Cyklotren measurements exhibit very high reproducibility (intraclass correlation coefficient [ICC] consistency ≥0.969, ICC agreement ≥0.965). It should be noted that the participant's position during IFmax measurements for both the elbow flexors and knee extensors was the same as during the 1RM test (Figure 1). Briefly, after warming up, each participant performed a 10 s maximal strength test for both elbow flexion and knee extension with the right and left extremities separately, with a 2-minute break between measurements. Estimated training loads were used during testing. The ranges of motion were approximately 130° for the elbow flexors and 80° for the knee extensors. The Cyklotren device displayed (on its screen) and recorded the force level for each repetition; the highest value of force (N) was used for future analysis.

2.4.3 Maximal voluntary torque (MVT) measurement

The maximal torque derived from isometric muscle actions was determined using a specialized Biodex 4 Pro device (Shirley, NY, United States). Measurement methodology was similar to presented by Bezulska et al. (2018). Data collection was preceded by a familiarization session. Biomechanical measurements were collected in a seated position. During elbow flexor measurements, the hand of the active arm grasped the device handle, while the other hand remained on the abdomen. The shoulder and elbow joints of the active arm were set at 90 degrees of flexion. During knee extensor measurements, the ankle of the active leg was attached to the Biodex 4 Pro device moving shin pad. In the starting position, the thigh of the active leg was immobilized at 90° in relation to the trunk, and the knee was also positioned at 90°. To prevent any activity of other muscle groups that were not being tested, the participant's trunk was stabilized using belts across the chest. Prior to the measurements, the participants were given verbal instructions regarding the experiment's design. Each participant performed three maximal isometric contractions (for each tested muscle group for both the upper and lower extremities), each lasting 3 s and separated by 30 s breaks. The highest value among the three trials was adopted for further analysis.

2.4.4 Jump tests

The vertical jump tests required each participant to perform three SJs (squat jumps), with a 30 s passive rest period between each effort, followed by three CMJs (countermovement jumps), with a 30 s passive rest period between each effort. Both the SJs and CMJs were performed using a TENDO JumpMat (Tendo Sports Machines, Trencin, Slovak Republic), jump mats can be successfully used to measure SJ and CMJ (Rogan et al., 2015). The highest of the three jump values (cm) was adopted for further analysis.

2.4.5 Upper limb strength—Pull-ups

There are several different grip pull-ups, we used the type called chin-up, which strongly engages the arm flexor muscles

(Johnson et al., 2009; Raizada and Bagchi, 2019). Participants grasped an overhead horizontal bar with their arms shoulder-width apart and forearms in the supinated position while hanging vertically (with feet just above the ground). The body was pulled upright in a linear path until the underside of the chin was level with or above the top surface of the horizontal bar. The participants were instructed to avoid all swinging, kicking, and twisting motions. Each participant had to perform as many repetitions as possible.

2.4.6 Body composition

To evaluate the influence of training on body composition, a bioelectrical impedance device (Tanita MC-980 MA; Tanita Corporation, Tokyo, Japan) was used. The participants were asked to maintain a normal state of hydration prior to the measurements, and they were not allowed to exercise or eat for 12 h preceding the measurements. The measurements were made in the morning according to the manufacturer's and Stahn et al. (2012) guidelines.

2.4.7 Limb circumference

Upper arm circumference was measured at the thickest part of the arm in the tensed muscle (Hu et al., 2021). Thigh circumference was determined at the midpoint of the thigh of the loaded leg (Fukuoka et al., 2024). The same researcher took three measurements, with each made to the nearest 0.5 cm. The mean value of the three measurements was used for future calculations.

Visualization of a research sequence is presented in Figure 2.

2.5 Statistical analysis

The Shapiro–Wilk test was used to test if the data were normally distributed. Descriptive statistics, including means and standard deviations, were calculated. A two-way analysis of variance (ANOVA) with repeated measures was used to determine the effect of exercises. If differences were detected, the Scheffé *post hoc* procedure was used to determine where the differences occurred. The level of significance was set at $P \leq 0.05$. The simple effect of training for each participant was defined as a relative increase in an analyzed variable after training compared with the value from before training. Lower and upper borders of 95% confidence intervals for relative increases were calculated. The effect size (ES) of the training was calculated using the independent two-sample *t*-test, and Cohen's d was calculated. The scale presented by Cohen (1988) indicates that $d < 0.41$ represents a low ES, 0.41–0.70 represents a moderate ES, and values greater than 0.70 represent a high ES.

3 Results

None of the analyzed parameters differed significantly between the two tested groups at the beginning of the experiment. Muscle strength (1RM) increased significantly following training in both groups. It increased by 15%–22.6% in IT and 21.3%–27.3% in TRT However, the differences in relative strength increases between the two trained groups were not significant (Table 1).

The IFmax of the elbow flexors increased significantly in both training groups, but the differences in relative force increases between IT and TRT were not significant. On the other hand, IFmax of the knee extensors increased significantly in IT only (by 19.7% and 27.1% in the right and left limbs, respectively), while changes in IFmax of the knee extensors in TRT were trivial (−2.75% and 1.73% in the right and left limbs, respectively). The relative increases noted in IT were significantly greater than in TRT, and the effect sizes expressed by Cohen's d value were large (Table 1).

MVT increased significantly in all trained muscles in both IT and TRT (Table 2). The relative increases in elbow flexor torque were similar between the two groups, but the relative increases in knee extensor torque were slightly greater in IT compared to TRT; however, the differences were not statistically significant (ES = 0.41 and 0.51 for the right and left limbs, respectively, indicating a moderate effect).

The height of CMJ and SJ increased significantly in both training groups, and there were no significant differences in relative changes between groups (Table 2).

Elbow flexor muscle strength, evaluated by the pull-up test, increased significantly in both trained groups, but once again, the differences in relative changes between the two groups did not differ significantly (Table 3).

Arm and thigh circumferences increased significantly following IT. However, in TRT, the circumference of the arms increased significantly, while changes in the circumference of the thighs were trivial (Table 3). The relative changes in the circumferences of the arms were similar between the two groups, but the relative changes in the circumferences of the thighs were significantly greater in IT than in TRT—ES = 2.13 and 2.04 for the right and left limbs, respectively.

Body composition did not change significantly in either training group.

4 Discussion

The results of this study indicate that changes in the elbow flexors following IT and TRT were similar. For every measurement condition (free weights, inertial conditions, isometric conditions, and pull-up test), strength levels increased significantly in both trained groups. There were no significant differences in relative strength increases between groups. In other words, the results showed that both types of training enhanced elbow flexor strength to a similar extent. No advantage to either training method was observed. To the best of our knowledge, no other studies have compared the effectiveness of inertial training vs. traditional resistance training in relation to elbow flexors. The relative increases in elbow flexor strength under inertial conditions in both groups were similar to those reported by Naczk et al. (2016b), who noted a 28.4% increase in elbow flexor strength after 5 weeks of inertial training.

Both inertial and traditional resistance training led to significant increases in knee extensor strength under free weight and isometric conditions, and the increases were similar in both groups. However, under inertial conditions, significant strength increases were noted in IT, while the TRT changes were trivial. Furthermore, ES showed an advantage for IT over TRT in strength enhancement under inertial conditions (ES = 1.51 and 1.59 for the right and left legs, respectively). It should be noted that considering the short training period (6 weeks), the increase in muscle strength (1RM

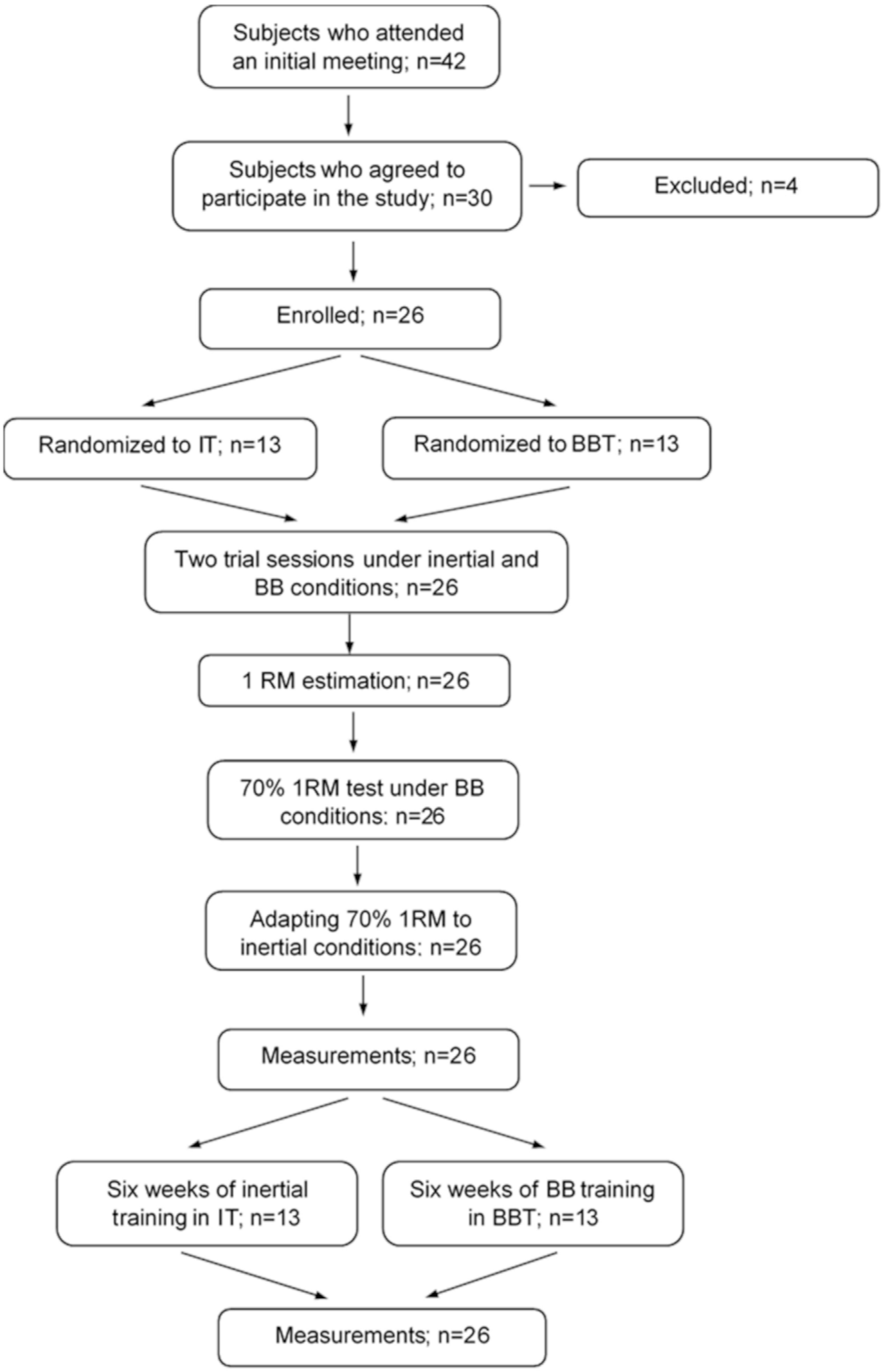

FIGURE 2
Flow diagram for study participants.

and IFmax) in the IT (from 15% to 29.9%) was large. Increase in strength following inertial training may from both improvement in neuromuscular coordination and muscle hypertrophy. Significant increase of EMG amplitude was observed in Naczk et al. (2016a) in young males after 5 weeks of inertial training. In other study significant increase in EMG amplitude was noted just after 3 weeks of training performed by young males (Seynnes et al., 2007). Changes in EMG suggesting that significant neural adaptations occurred in response to the training stimulus and possibly indicating recruitment of higher threshold motor units. Moreover, Seynnes et al. (2007) can observed significantly increased quadriceps cross-sectional area just after 3 weeks of inertial training. Fast muscle mass increases may be due to a strong eccentric phase, which occurs during inertial training; eccentric contractions elicit greater muscle hypertrophy than concentric (Roig et al., 2009). However, the strength increases noted in IT under static conditions were not

TABLE 1 Mean and standard deviations for absolute values of 1RM and maximal force measured under inertial conditions.

Group/ muscle		1RM [kg]				IFmax [N]			
		EF		KE		EF		KE	
Limb		R	L	R	L	R	L	R	L
IT	Before	18.2 ± 1.71	17.9 ± 1.70	43.5 ± 5.33	43.5 ± 4.96	144 ± 19.6	144 ± 17.5	387 ± 66.9	385 ± 65.1
	95% CI	17.3–19.1	17.0–18.8	40.6–46.4	40.8–46.2	133–155	134–154	351–423	350–420
	After	20.9 ± 2.59*	20.8 ± 2.32*	53.5 ± 8.23*	53.5 ± 8.29*	185 ± 22.0*	185 ± 22.0*	460 ± 72.0*	488 ± 87.5*
	95% CI	19.5–22.3	19.5–22.1	49–58	49–58	173–197	173–197	421–499	440–536
	% change	15.0 ± 12.5	17.2 ± 14.7	22.3 ± 10.3	22.6 ± 9.93	29.8 ± 15.0	29.9 ± 16.0	19.7 ± 10.5#	27.1 ± 13.7#
IT vs. TRT	ES	0.55	0.28	0.32	0.31	0.38	0.30	1.51	1.59
TRT	Before	17.6 ± 2.43	17.6 ± 2.43	39.7 ± 6.53	39.4 ± 6.53	135 ± 22.8	135 ± 22.8	360 ± 59.1	367 ± 47.1
	95% CI	16.3–18.9	16.3–18.9	36.2–43.3	35.9–42.9	123–147	123–147	328–392	341–393
	After	21.3 ± 3.05*	21.2 ± 2.78*	49.8 ± 7.03*	49.4 ± 8.09*	164 ± 23.3*	166 ± 23.6*	343 ± 44.9	371 ± 65.1
	95% CI	19.6–23	19.7–22.7	46–53.6	45–53.8	151–177	153–179	319–367	336–406
	% change	21.8 ± 11.3	21.3 ± 13.9	27.0 ± 17.0	27.3 ± 17.9	23.7 ± 16.0	25.1 ± 14.6	−2.75 ± 17.4	1.73 ± 17.0

Notes: EF, elbow flexion; KE, knee extension; R, right limb; L, left limb; ES, effect size between groups,*- significant difference from baseline, # - significant difference between groups ($P \leq 0.05$).

TABLE 2 Mean and standard deviations for absolute values of MVT, CMJ, SJ, and maximal Pull-up test.

		MVT [nm]						
		EF		KE		CMJ [cm]	SJ [cm]	Pull-up [rep]
		R	L	R	L			
IT	Before	77.7 ± 10.1	72.4 ± 8.09	312 ± 57.9	277 ± 44.2	40.3 ± 5.60	32.7 ± 4.55	8.62 ± 5.06
	95% CI	72.2–83.2	68–76.8	281–344	253–301	37.3–43.3	30.2–35.2	5.87–11.4
	After	86.8 ± 12.4*	81.6 ± 12.0*	360 ± 58.1*	342 ± 60,3*	42.5 ± 3.72*	35.1 ± 3.80*	12.9 ± 5.86*
	95% CI	80.1–93.5	75.1–88.1	328–392	309–375	40.5–44.5	33–37.2	9.71–16.1
	% change	12.1 ± 12.1	12.7 ± 10.7	16.3 ± 10.1	23.6 ± 12.8	6.28 ± 8.10	7.95 ± 9.75	49.6 ± 36.2
IT vs. TRT	ES	0.27	0.02	0.41	0.51	0.17	0.32	0.41
TRT	Before	73.1 ± 10.6	68.5 ± 9.37	278 ± 54.2	270 ± 54.8	35.3 ± 6.25	29.6 ± 5.69	10.9 ± 5.28
	95% CI	67.3–78.9	63.4–73.6	249–308	240,300	31.9–38.7	26.5–32.7	8.03–13.8
	After	78.9 ± 10.7*	77.2 ± 12.3*	307 ± 53.5*	315 ± 67.1*	37.2 ± 7.86*	32.7 ± 6.34*	14.8 ± 6.92*
	95% CI	73.1–84.7	70.5–83.9	278–336	279 to 352	32.9–41.5	29.3–36.2	11–18.6
	% change	8.8 ± 11.7	12.9 ± 11.2	11.6 ± 12.2	17.2 ± 11.3	4,89 ± 7.40	11.0 ± 8.53	35.8 ± 27.6

Notes: EF, elbow flexion; KE, knee extension; R, right limb; L, left limb; ES, effect size between groups,*- significant difference from baseline, # - significant difference between groups ($P \leq 0.05$).

TABLE 3 Circumferences of the limbs.

		Circumferences of the limbs			
		Arms		Thighs	
		R	L	R	L
IT	Before	33.4 ± 2.99	33.2 ± 4.38	53.9 ± 3.60	53.9 ± 3.54
	95% CI	31.8–35	30.8–35.6	51.9–55.9	52–55.8
	After	34.4 ± 2.67*	34.4 ± 2.72*	55.1 ± 3.45*	55.0 ± 3.32*
	95% CI	32.9–35.9	32.9–35.9	53.2–57	53.2–56.8
	% change	3.23 ± 2.74	3.73 ± 2.92	2.13 ± 1.53#	2.04 ± 1.75#
IT vs. TRT	ES	0.09	0.10	1.38	1.15
TRT	Before	32.8 ± 2.77	32.6 ± 2.74	54.3 ± 4.04	54.2 ± 4.10
	95% CI	31.3–34.3	31.1–34.1	52.1–56.5	52–56.4
	After	33.9 ± 2.76*	33.9 ± 2.69*	54.5 ± 4.19	54.4 ± 4.15
	95% CI	32.4–35.4	32.4–35.4	52.2–56.8	52.1–56.7
	% change	3.44 ± 1.46	4.01 ± 2.27	0.34 ± 0.90	0.35 ± 0.99

Notes: R, right limb; L, left limb; ES, effect size between groups,*- significant difference from baseline, # - significant difference between groups (P ≤ 0.05).

significantly greater than those in TRT, although ES indicated a slightly greater effect of inertial training compared to traditional resistance training (moderate ES according to Cohen (1988)). The strength improvements noted in IT (MVT = 16.3–23.6%) were greater than those observed by Onambélé et al. (2008), who reported an 8% increase in their inertial training group. Conversely, the improvements in TRT that we found in our study were similar to those reported by Onambélé et al. (2008), in their G-Weight group (traditional training). It should be mentioned that the cited authors trained elderly participants over a 12-week period. Our participants achieved greater improvements in knee extensor muscle strength than those observed by de Hoyo et al. (2015), who reported approximately 5% and 10% increases in maximal isometric voluntary contraction following traditional and inertial training, respectively. It should be noted, however, that body position, range of motion, and movement techniques in the two groups trained by de Hoyo et al. (2015) were different. The influence of traditional and inertial training on knee extensor muscle strength was also tested by Greenwood et al. (2007). They concluded that inertial training appeared to be as effective as standard resistance training for improving knee extensor muscle performance after knee injuries. However, in our opinion, the estimation of training loads for each training group was different.

Both training methods significantly improved vertical jump performance. Relative increases in CMJ and SJ in TRT and IT were similar. Improvement in jump tests may result both improvement in neuromuscular coordination and muscle hypertrophy. Moreover, may also result from increased muscle tendon stiffness (Onambélé et al., 2008), improvement of the stretch-shortening cycle (Bosco et al., 1981) and increase in the excitability threshold of the Golgi tendon organs (McNeely and Sandler, 2007). Similar improvement in CMJ and SJ in both groups noted in our study is contrary to results of de Hoyo et al. (2015), who stated that traditional training caused significantly greater improvement than horizontal inertial flywheel training. It can be caused by different movement technique and range of motion used during training in two groups of participants trained by de Hoyo et al. (2015) The traditional training group performed the half squat exercise on a smith machine when inertial training group performed a front step exercise using an inertial flywheel. Half squat training technique was similar to the CMJ technique. Therefore, the strength transfer to CMJ after half squat training was easier to achieve comparing to strength transfer from front step exercise. In our study movement technique and range of motion during training in both training groups were the same. Arm circumference increased significantly in both TRT and IT, while thigh circumference increased significantly in IT only (ES = 1.38 and 1.15 for the right and left thighs, respectively). This suggests that inertial training stimulated knee extensor hypertrophy more than traditional weight training. This is consistent with Norrbrand et al. (2008) and Norrbrand et al. (2010) conclusions; they stated that the greater mechanical stress that occurs during inertial training compared to traditional strength training may explain the robust muscle hypertrophy in response to inertial training. In general, both types of training were effective in relation to the tested parameters. Our results indicate that inertial training was as effective as traditional resistance training when the elbow flexors were considered. Our data are consistent with Vicens-Bordas et al. (2018a), who stated that inertial flywheel resistance training and gravity-dependent resistance training improved muscle strength to a similar degree. However, in relation to knee extensor muscle strength, inertial training appeared to be slightly more effective than traditional resistance training. Among the six tested parameters (1RM, IFmax, MVT, CMJ, SJ, and limb circumference), two improved significantly more in IT compared to TRT (IFmax and thigh circumference). Moreover, the ES for MVT under isometric conditions was moderate, with a slight advantage for inertial training over traditional resistance training. This suggests that the effectiveness of the two types of training may vary depending on the different muscle groups being evaluated. We tested only two muscle groups, so future studies of other muscle groups are needed.

5 Limitations of the study

There are limitations to this study. First was described in methods section and concerning estimation of training loads and training protocols. Moreover, the training loads were not re-assessed throughout the training. Even though the procedure of estimating 1RM is quick and easy, estimating the training load in IT would have been fatiguing, which could have had a negative impact on the training process. Moreover, the study was conducted on a small group of participants. A small sample size limits the possibility of drawing strong conclusions. Second, we tested only two muscle groups (elbow flexors and knee extensors); it would be interesting to test the influence of the two training methods on other muscle groups. Another limitation of this research is its lack of data regarding longitudinal effects. We could not further evaluate the participants after the project was completed because of COVID-19 lockdowns. It would be interesting to evaluate how long the inertial and resistance training effects would be retained.

6 Conclusion

It can be stated that both types of training are highly effective in young physically active men, but the superiority of inertial training over traditional resistance training cannot be confirmed definitively, as Maroto-Izquierdo et al. (2017b) suggested in their review. Nevertheless, inertial training had a slight advantage over traditional resistance training when knee extensor muscle training was considered. It should be noted, the lack of definitive evidence that inertial training is superior to traditional resistance training does not mean that inertial training has no value as a training method. On the contrary, it is a very effective and useful training method for enhancing the locomotor system for sports (Davison et al., 2010; Maroto-Izquierdo et al., 2017a; Naczk et al., 2017) and rehabilitation (Fernandez-Gonzalo et al., 2016; Naczk et al., 2020; Naczk et al., 2022; Sarmiento et al., 2014). According to training principles for long-term training processes, varying training methods is often beneficial (Haff and Triplett, 2016). It is possible that inertial training can be a positive variation in one's training regime when a plateau is reached. This is supported by Naczk et al. (2017), who concluded that even well-trained swimmers can significantly improve their muscle strength in a relatively short time by implementing a new variation to their training regime-inertial training. Nevertheless, the methodology of inertial training requires further development.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Bioethical Commission of Collegium Medicum, University of Zielona Gora Affiliation: University of Zielona Gora. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

AN: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Writing–original draft, Writing–review and editing. KK-S: Conceptualization, Investigation, Methodology, Writing–original draft. EG: Conceptualization, Data curation, Formal Analysis, Writing–original draft. PG: Conceptualization, Resources, Software, Validation, Writing–original draft. TJ: Investigation, Writing–original draft. MN: Conceptualization, Investigation, Methodology, Resources, Supervision, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Impact of a brief series of soccer matches on vascular conditions in youth women

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Background: Accumulative excessive physical load elevates central arterial stiffness and smooth muscular tone of peripheral vascular beds in endurance athletes. The aim of this study was to test the hypothesis that a brief series of soccer matches would increase central arterial stiffness and arterial wave reflection from the periphery in young female football players.

Methods: Fifteen subjects (17.2 ± 0.7 years, mean ± SD) participated in four matches over five consecutive days (one match per day, with two consecutive days of matches followed by one rest day, repeated twice) in the Youth Girls Soccer Tournament, either as starters or substitutes. Heart rate, blood pressure (BP), and the second derivative of the photoplethysmogram (SDPTG) were assessed the night before and 4 h after each match. The ratios of the first and second descending waves to the first ascending wave of SDPTG (B/A ratio and D/A ratio) were calculated as indices of central arterial stiffness and peripheral wave reflection, respectively. The intra-individual relationship among interest variables was evaluated using the repeated-measures correlation analysis (rmcorr).

Results: Post-match D/A ratio, systolic and diastolic BP were lower compared to the pre-match value, while the B/A ratio did not change significantly. Heart rate was higher post-than pre-match. Rmcorr demonstrated significant intra-individual correlations of the D/A ratio with diastolic BP (r_{rm} = 0.259, P = 0.008) and heart rate (r_{rm} = −0.380, P< 0.001).

Conclusion: Contrary to our hypothesis, a brief series of matches did not increase central arterial stiffness in young female football players. Instead, the matches induced a repeated, temporary attenuation of arterial wave reflection. This attenuated arterial wave reflection from the periphery appeared to be associated with reduced diastolic BP and a compensatory increase in heart rate.

KEYWORDS

finger photoplethysmogram, arterial stiffness, wave reflection, soccer, women, repeated-measures correlation analysis

1 Introduction

Accumulative excessive physical load increases central arterial stiffness and smooth muscular tone in the peripheral vascular beds of endurance athletes, likely due to enhanced sympathetic nervous activity and oxidative stress (Iellamo et al., 2002; Knez et al., 2006; Barnes et al., 2010; Vlachopoulos et al., 2010). We previously reported that, in well-trained male collegiate endurance runners, aortic systolic and pulse pressures, along with central arterial stiffness, increased after a 7-day intense endurance training camp, with these changes correlating to the total running distance (Tomoto et al., 2015; 2018). Therefore, the vascular condition—characterized by central arterial stiffness and peripheral vascular smooth muscle tone—may reflect exercise-induced physiological fatigue and recovery.

It should be noted that postexercise hemodynamic responses to acute endurance exercise bouts differ between men and women (Senitko et al., 2002). However, our studies subjected male-only groups, and thus, the hemodynamic response to repeated, intense endurance exercise bouts in women is not entirely known.

A photoplethysmogram (PTG) measures changes in the absorbance of hemoglobin based on the Lambert–Bernstein law, indicating regional blood flow (Jespersen and Pedersen, 1986). The waveform, recorded at the finger, has two main components: an early systolic wave caused by left ventricular ejection, and a reflected wave from the periphery (Westerhof et al., 1972a; Hashimoto et al., 2002). These components could be characterized by the five inflection points on PTG waves using second derivatives (e.g., SDPTG). This technique provides a composite measure of vascular aging (Takazawa et al., 1998), and the detailed wave analysis offers surrogate markers for both central arterial stiffness and peripheral vascular smooth muscle tone (Westerhof et al., 1972b; Hashimoto et al., 2002). Thus, it is a valuable tool for assessing the vascular condition of athletes.

Athletes competing at higher levels require intense, high-volume training, which often results in prolonged imbalances between fatigue and recovery. This can reduce trainability, impair performance, and increase the risk of overtraining syndrome (Lee et al., 2017). Ideally, the relationship between training load and physiological responses should be monitored individually. However, much of the current evidence is based on cross-sectional studies, which fail to capture intra-individual changes over time (Lee et al., 2017). Additionally, conventional correlation analysis applied to repeated measures can produce biased results due to non-independent observations (Bakdash and Marusich, 2017).

In this field study, we sought to identify sensitive vascular biomarkers that reflect physical fatigue and recovery in athletes. We aimed to elucidate the impact of a brief series of matches on vascular conditions in young female soccer players. Additionally, we determined the relationship between intra-individual responses of vascular condition, hemodynamics, and fatigue to the repetitive matches using the repeated measures correlation analysis (Bakdash and Marusich, 2017). Given that the required running speed and distance in soccer vary depending on a player's position and the strength of the opposing team, this approach allowed us to efficiently clarify the individual relationship between physical fatigue and vascular responses. We hypothesized that a brief series of soccer matches would increase central arterial stiffness and arterial wave reflection from the periphery in young female football players, correlating with fatigue, and that this vascular condition would be associated with hemodynamic markers such as blood pressure and heart rate.

2 Methods

2.1 Participants

Fifteen female football players (mean age: 17.2 ± 0.7 years) participating in the Youth Girls Soccer Tournament (XF CUP 2021 Japan Club Youth U18) underwent evaluation. None of the participants had cardiovascular, cerebrovascular, and respiratory disease. All participants were not taking any prescribed or over-the-counter medications or supplements. All procedures conformed to the Declaration of Helsinki (Seventh revision, 64th Meeting, Fortaleza, 2013) and were approved by the Institutional Review Board at Toyo University (Approval Number: TU 2021-022). Th e participants (or parents/guardians) provided written informed consent before participation.

2.2 Experimental procedure

All subjects participated in four matches over five consecutive days (one match per day, with two consecutive days of matches followed by one rest day, repeated twice) in the Youth Girls Soccer Tournament, either as starters or substitutes. Throughout the tournament period, the following measurements were performed before night and approximately 4 h after each match (Figure 1). These measurement timings correspond to 2 h after dinner and 2 h after lunch. Body weight and fat (via a digital scale for body weight, TANITA, Japan), single isometric knee extension strength (KES, via a goniometer, mobie MT-100 and -250; Sakai Medical, Tokyo, Japan), and the rate of perceived exertion (RPE) were also measured. RPE was evaluated by the visual analog scale. Each participant marked their subjective whole body fatigue level on a 100 mm black line (the left end is "0" and the right end is "100").

2.3 Vascular measurements

After 5 min of quiet sitting on the chair, hemodynamic variables were collected in the same posture. All participants underwent heart rate (Bedside monitor BMS-3400; Nihon Kohden, Tokyo, Japan), blood pressure (Intellisense, Omron Healthcare, Kyoto, Japan), and PTG recordings. Stable pulse waveforms were stored for 30 s on the right index finger with a customized fingertip Photoplethysmography (Alps, Tokyo, Japan) and calculated the second Derivative waveform of PTG (i.e., SDPTG) using an optimized software (AGVS monitor, Alps, Tokyo, Japan). The methodology details for measuring PTG and SDPTG are reported (Takazawa et al., 1998; Fukuie et al., 2021). The SDPTG provides 5 specific inflection points on PTG waves such as the initial positive wave ("a" wave), an early negative wave ("b" wave), a re-increasing wave ("c" wave), a late re-decreasing wave ("d" wave), and a diastolic positive wave ("e" wave) (Figure 2). The amplitude

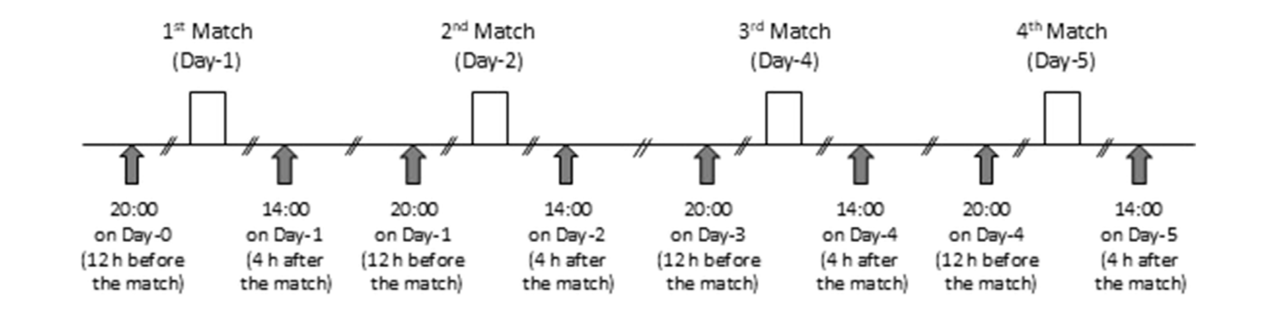

FIGURE 1
Experimental timeline.

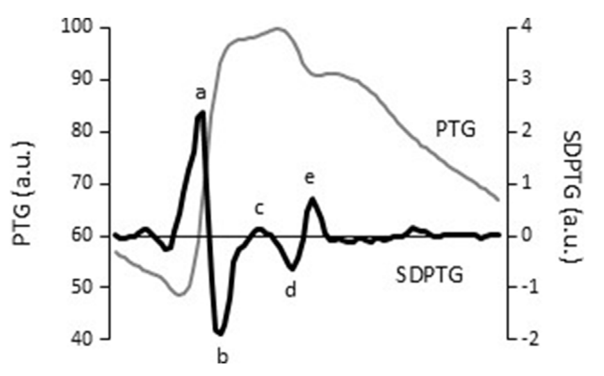

FIGURE 2
Sample signals of finger photoplethysmogram (PTG, grey line) and the second derivative of the finger photoplethysmogram (SDPTG, black line). Letters of "a" - "e" indicate five inflection points on finger PTG waves characterized by the SDPTG: the initial positive (a), early negative (b), re-increasing (c), late re-decreasing (d), and diastolic positive waves (e).

ratio of the early negative wave ("b" wave) to the initial positive wave ("a" wave) (i.e., B/A ratio) is assumed as the index of central arterial stiffness, whereas that of the late re-decreasing wave ("d" wave) to the "a" wave (i.e., D/A ratio) is closely related to the intensity of wave reflection from the periphery, and thus, peripheral vascular tone (Westerhof et al., 1972b; Hashimoto et al., 2002). The validation of this automatic device and its reproducibility have been reported previously, with an excellent intra-observer reproducibility evaluated by intraclass correlation (B/A ratio = 0.868, D/A ratio = 0.793, vascular age = 0.914) (Fukuie et al., 2021).

2.4 Statistical analysis

All the analyses were conducted with IBM SPSS Statistics (ver. 29.0, IBM Corp., Chicago, IL) and RStudio (2023.09.1 Build 494, Posit Software, PBC). The P-values <0.05 were considered to denote statistical significance. The linear mixed model (LMM), which can appropriately handle cases where some data is missing within repeated measures, was used to analyze the main and interaction effects of the match (the first to fourth matches) and time (pre-vs post-match) on body weight, hemodynamic variables, KES, and RPE. Post hoc analysis using Bonferroni corrections was applied when main factors or interactions were significant. Data are expressed as estimated marginal means and 95% confidential intervals. The intra-individual relationship among interest variables was evaluated using the repeated-measures correlation analysis (rmcorr) using the R package (Bakdash and Marusich, 2017).

3 Results

During the experimental period, there were a total of two instances of missing data for both B/A and D/A ratios. Additionally, there were four instances of missing data for RPE and seven instances for KES. Therefore, estimated marginal means and 95% confidence intervals were reported using LMM. As shown in Table 1, body weight was lower (time effect: $P< 0.0001$), and RPE was higher (time effect: $p = 0.001$) post-match compared with pre-match. KES tended to be lower post-match than pre-match (time effect: $p = 0.084$).

Figure 3 depicts comparisons of the estimated marginal means (via linear mix model) of hemodynamic and SDPTG indices between pre- and post-match. Heart rate was higher (time effect: $p = 0.019$). Systolic and diastolic BP, and D/A ratio were lower than the pre-match value (time effects: $p = 0.021$, $p = 0.016$, and $p = 0.023$, respectively). The B/A ratio did not show a significant change over time ($p = 0.653$). However, the D/A ratio exhibited a significant effect related to the match sequence ($p = 0.009$). The D/A ratio at the third and fourth matches was lower than that at the first (Bonferroni test: $p = 0.027$ and 0.031). Rmcorr revealed that the D/A ratio exhibited significant intra-individual correlations with KES ($r_{rm} = 0.200$, $p = 0.049$) and RPE ($r_{rm} = -0.229$, $p = 0.022$) (Figure 4). Furthermore, the D/A ratio demonstrated significant intra-individual correlations with diastolic BP ($r_{rm} = 0.259$, $p = 0.008$) and heart rate ($r_{rm} = -0.381$, $P< 0.001$) (Figure 5). However, no significant correlation was found with systolic BP ($r_{rm} = 0.155$, $p = 0.118$).

4 Discussion

The main findings of the present study are as follows: first, during the daily repetition of soccer matches, the post-match values of the D/A ratio and BP were lower than the pre-match values, while the B/A ratio showed no significant changes. Second, the D/A ratio

TABLE 1 Responses of physiological indices to the repetitive soccer matches.

	Match	Pre-match		Post-match		P-value for	
		EMM	95% CI	EMM	95% CI	Linear Mix Model	
Body weight	1st	53.5	(51.2–55.8)	52.7[b]	(50.4–55.0)	Match	**0.007**
kg	2nd	53.1	(50.8–55.4)	52.7[b]	(50.4–55.0)	Time	**<0.0001**
	3rd[a]	52.7	(50.4–55.0)	52.6	(50.3–54.9)	Interaction	**0.017**
	4th	53.4	(51.1–55.7)	52.8[b]	(50.5–55.1)		
KES	1st	29.8	(24.9–34.7)	27.8	(23.1–32.5)	Match	0.942
kg	2nd	30.0	(26.7–33.4)	26.4	(21.7–31.2)	Time	0.084
	3rd	28.4	(23.6–33.2)	28.6	(23.9–33.3)	Interaction	0.384
	4th	28.9	(24.1–33.7)	27.5	(22.8–32.3)		
RPE	1st	46.6	(38.1–33.7)	60.5	(52.1–68.9)	Match	0.017
a.u.	2nd	54.5	(46.1–62.9)	71.9	(63.6–80.1)	Time	**0.001**
	3rd	51.2	(42.9–59.4)	68.5	(60.3–76.8)	Interaction	0.158
	4th	59.5	(51.3–67.8)	67.8	(59.6–76.1)		
Heart rate	1st	68	(63–73)	73	(68–78)	Match	0.725
bpm	2nd	65	(61–70)	73	(68–78)	Time	**0.019**
	3rd	68	(63–73)	73	(68–78)	Interaction	0.476
	4th	68	(63–73)	70	(65–75)		
Systolic BP	1st	111	(105–116)	103	(97–109)	Match	0.700
mmHg	2nd	106	(100–112)	105	(99–110)	Time	**0.021**
	3rd	107	(101–113)	106	(100–111)	Interaction	0.267
	4th	106	(100–112)	102	(96–108)		
Diastolic BP	1st	67	(62–72)	58	(53–63)	Match	0.854
mmHg	2nd	61	(56–66)	61	(56–66)	Time	**0.016**
	3rd	62	(57–67)	61	(56–66)	Interaction	0.099
	4th	64	(59–69)	60	(55–65)		
B/A ratio	1st	0.73	(0.66–0.79)	0.76	(0.70–0.83)	Match	0.548
a.u.	2nd	0.82	(0.76–0.88)	0.77	(0.71–0.83)	Time	0.653
	3rd	0.78	(0.71–0.84)	0.77	(0.71–0.83)	Interaction	0.383
	4th	0.77	(0.71–0.83)	0.75	(0.69–0.82)		
D/A ratio	1st	0.25	(0.19–0.32)	0.19	(0.12–0.25)	Match	**0.009**

(Continued on the following page)

TABLE 1 (*Continued*) Responses of physiological indices to the repetitive soccer matches.

	Match	Pre-match		Post-match		P-value for	
		EMM	95% CI	EMM	95% CI	Linear Mix Model	
a.u.	2nd	0.23	(0.16–0.29)	0.15	(0.08–0.22)	Time	**0.023**
	3rd[a]	0.14	(0.08–0.21)	0.14	(0.07–0.20)	Interaction	0.134
	4th[a]	0.19	(0.13–0.26)	0.10	(0.03–0.17)		

EMM, estimated marginal mean; CI, confidential interval; KES, single isometric knee extension strength; BP, blood pressure.
[a]Significant difference vs. 1st match.
[b]Significant difference vs. pre-match.

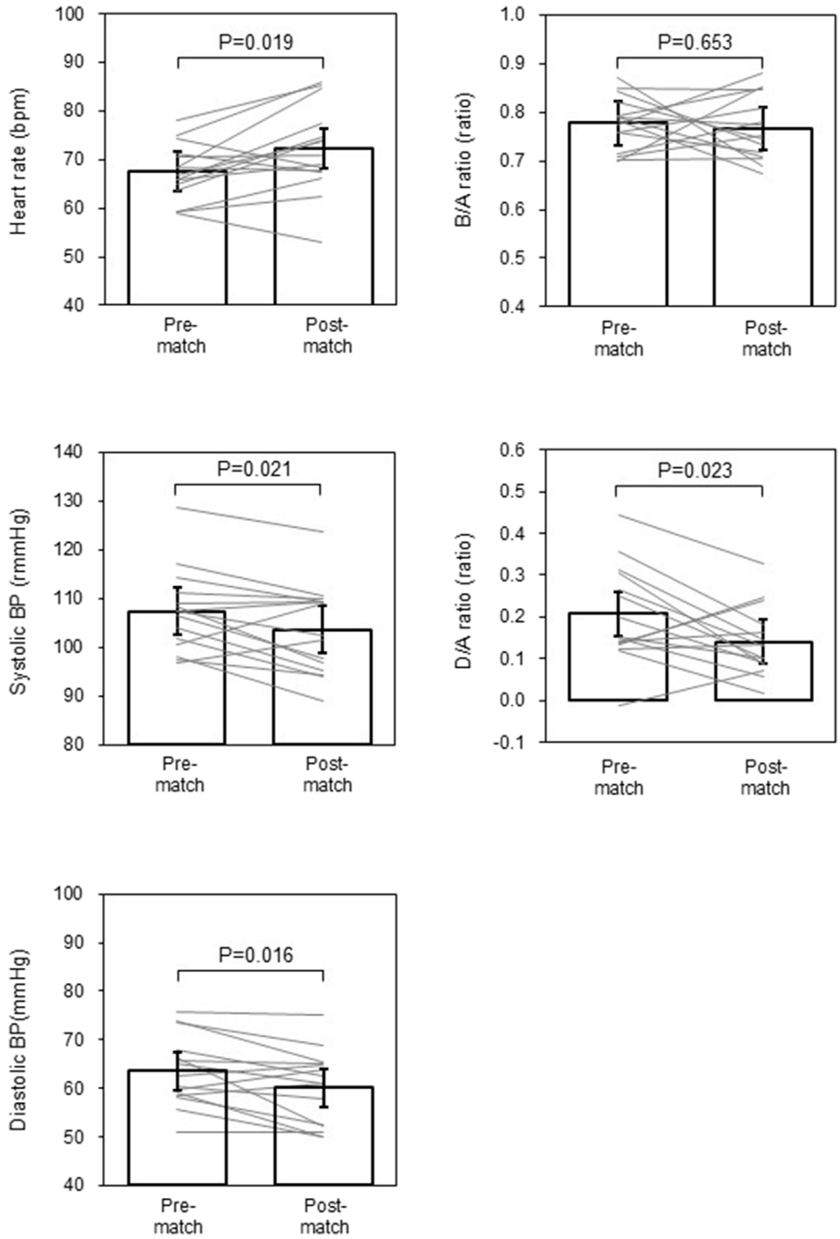

FIGURE 3
Hemodynamic variables and the second derivative of the finger photoplethysmogram indices pre- and post-match. Data are estimated marginal means and 95% of confidential intervals. Grey lines indicate changes in individual estimated marginal mean.

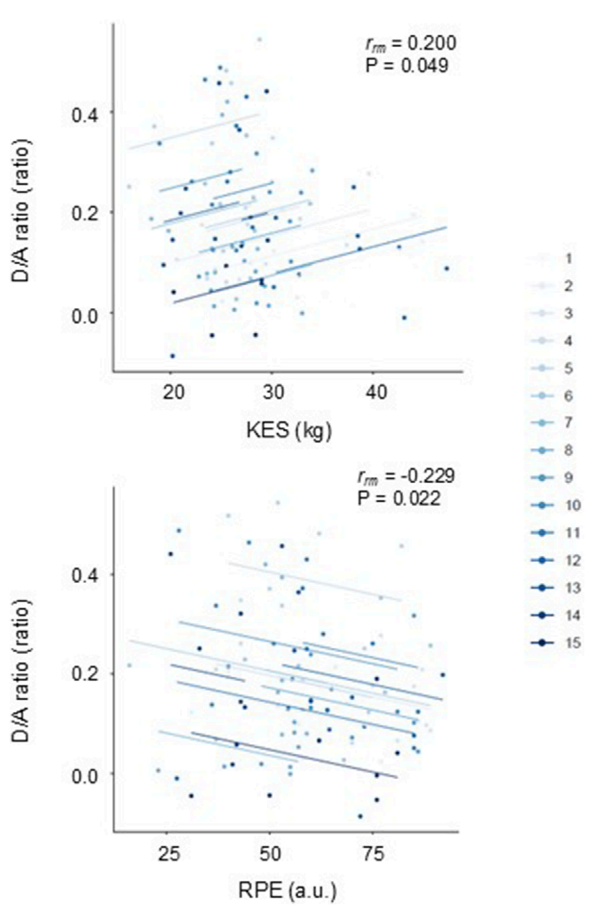

FIGURE 4
Repeated measures correlation plots of the single isometric knee extension strength (KES) (*top panel*) and the rate of perceived exertion (RPE) (*bottom panel*) with the D/A ratio.

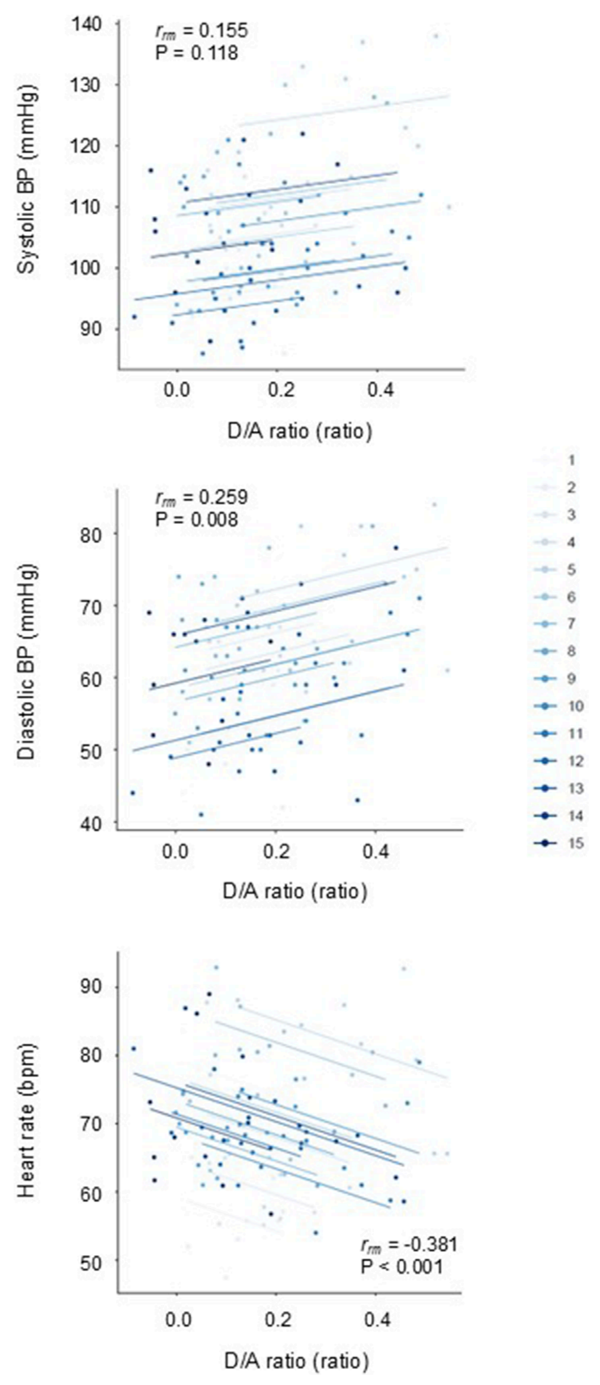

FIGURE 5
Repeated measures correlation plots of the D/A ratio with diastolic blood pressure (BP) (*top panel*) and heart rate (*bottom panel*).

exhibited significant intra-individual correlations with diastolic BP and heart rate. These results suggest that, in young female football players, a brief series of matches did not increase central arterial stiffness but instead led to a repeated, temporary attenuation of arterial wave reflection, which was associated with a reduction in diastolic BP and a compensatory rise in heart rate.

In young female football players who engaged in a brief series of matches, the D/A ratio was lower 4 h after the soccer matches compared with that the night before the matches, suggesting that the attenuated arterial wave reflection lasted more than 4 h, followed by gradual recovery. Rmcorr indicated that the D/A ratio had significant intra-individual relationships with the indices of fatigue (i.e., KES and RPE). While the level of fatigue likely varied individually depending on each player's position and the strength of the opposing team, the series of matches consistently induced repeated, temporary attenuation of arterial wave reflection, which was associated with physical exertion in each individual.

We found mild hypotension in our subjects after the matches, as depicted in Figure 3. Specifically, the D/A ratio exhibited a significant intra-individual correlation with diastolic BP but not with systolic BP. While systolic BP is influenced by several hemodynamic factors, including arterial stiffness, stroke volume, and left ventricular ejection fraction, the primary hemodynamic determinants of diastolic BP include total peripheral resistance, heart rate, arterial stiffness, and systolic BP (Tanaka et al., 2016). It is important to note that postexercise hemodynamic responses to acute endurance exercise bouts differ between men and women. Endurance-trained women typically experience postexercise hypotension due to a persistent reduction in systemic vascular resistance, whereas endurance-trained men showed a substantial drop in cardiac output with unchanged systemic vascular resistance (Senitko et al., 2002). Therefore, the prolonged reduction in peripheral vascular tone may explain the postexercise hypotension in our subjects.

Exaggerated hypotension may be unfavorable for normotensives. Orthostatic hypotension, a hemodynamic malregulation, is often observed following endurance exercise (Mundel et al., 2015) and in women (Bryarly et al., 2019), mainly due to peripheral blood pooling and insufficient offset by increases in cardiac output. It may precipitate lightheadedness, dizziness, fatigability, and presyncope (Ma et al., 2024). Fortunately, no one complained of unfavorable hypotension-related symptoms. We could speculate on the contribution of tachycardia as an underlying mechanism. The increase in heart rate lasted 4 h after the match, as did the decrease in the D/A ratio. In addition, the individual response of the D/A ratio is inversely correlated with that of heart rate, as shown in Figure 5. Thus, the increase in heart rate may partly compensate for the prolonged reduction in systemic vasodilation after the soccer match, not to drop BP substantially.

In contrast to the D/A ratio, the B/A ratio did not change significantly during the observation period. The B/A ratio seems to be associated with central arterial stiffness (Westerhof et al., 1972a; Hashimoto et al., 2002), which typically reduces 30–60 min after moderate-intensity endurance exercise (Kingwell et al., 1997). Since we did not assess SDTPG indices within a couple of hours after the soccer match, it remains uncertain whether the B/A ratio might decrease tentatively and return to the baseline level by 4 h post-match. Our previous research on well-trained male collegiate endurance runners demonstrated increased arterial stiffness and elevated aortic systolic and pulse pressures after a 7-day intense endurance training camp (Tomoto et al., 2015; 2018), reflecting heightened vascular tone after short-term, intense endurance training. However, the current study suggests a gradual decrease in peripheral vascular smooth muscle tone without significant changes in central arterial stiffness after repeated soccer matches. Taken together, these findings imply that peripheral vascular tone is more sensitive to physical exertion than central arterial stiffness in endurance-trained females.

4.1 Significance and perspectives

An adequate balance between fatigue (derived from training and competition load) and recovery is essential for athletes to accomplish high-level training and achieve high-level performance continuously. Therefore, systematic monitoring of athletes' condition is essential for their performance and for preventing adverse outcomes such as under-recovery, nonfunctional overreaching, overtraining syndrome, injuries, or illnesses (Kellmann et al., 2018). The rapid and accurate collection of physiological responses to the single and repetitive exercise load may contribute to getting useful markers for athletic conditioning. Given the simplicity of the technique, SDPTG assessment holds promise as a technique suitable for routine self-monitoring of athletes' vascular conditions. In the present study, the reduction of the D/A ratio was seen not only post-match but also at the second 2-consecutive match (vs the first match). It is likely to be associated with accumulated fatigue. Future research should further explore the response of the D/A ratio as a biomarker for under-recovery and nonfunctional overreaching due to prolonged excessive exercise training.

4.2 Limitations

Required running speed and distance vary in each position. Furthermore, opposing teams are different in each match. Because of its nature, we cannot control individual physiological load and fatigue. Furthermore, this study did not involve the sedentary control group. However, through repeated measures correlation analysis, we were able to clearly demonstrate the impact of accumulated fatigue on individual vascular conditions. Lastly, the results of this study are specific to young female athletes, and it remains unclear if these findings would be applicable to male athletes or different age groups.

5 Conclusion

A brief series of matches in young female football players induced the repeated, temporary attenuation of arterial wave reflection, which was associated with reduced diastolic BP and a compensatory increase in heart rate.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Institutional Review Board at Toyo University (Approval Number: TU 2021-022). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

JS: Formal Analysis, Funding acquisition, Investigation, Methodology, Writing–original draft, Writing–review and editing. NO: Data curation, Formal Analysis, Investigation, Writing–review and editing. HW: Data curation, Formal Analysis, Investigation, Writing–review and editing. SS: Data curation, Formal Analysis, Investigation, Writing–review and editing. MO: Investigation, Project administration, Supervision, Writing–review and editing. TH: Investigation, Project administration, Supervision, Writing–review and editing. NK: Investigation, Writing–review and editing. SO: Conceptualization, Data curation, Formal Analysis, Investigation, Project administration, Supervision, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Can trainability constrain physical fitness adaptations to small-sided games and high-intensity interval training in young male basketball players? a prospective cohort study

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Introduction: Research on the effects of training programs involving small-sided games (SSG) versus high-intensity interval training (HIIT) has been increasing in recent years. However, there is limited understanding of how an individual's initial physical fitness level might influence the extent of adaptations achieved through these programs. This study aimed to compare the impacts of SSG and HIIT on male soccer players, while also considering the players' athleticism, categorized into lower and higher total athleticism score (TSA).

Methods: A prospective cohort study was conducted over a 6-week pre-season training period, involving 43 male soccer players from regional-level teams (average age 16.5 ± 0.7 years). Players were evaluated at the start and after the 6-week period. One team incorporated SSG as a core component of their aerobic-based training, while the other team used HIIT. Evaluations included a countermovement jump (CMJ) test, a 30-meter linear sprint test, and the 30–15 intermittent fitness test (30–15 IFT). TSA was calculated to assess each player's overall athleticism level (classifying them as fit and non-fit).

Results: Results revealed that non-fit players showed significantly greater CMJ improvements (mean difference: 3.0 cm; $p < 0.005$) and VIFT improvements (mean difference: 0.682 km/h; $p = 0.002$) in SSG compared to fit players. In the HIIT group, non-fit players also revealed greater improvements than fit players in CMJ (mean difference: 2.5 cm; $p < 0.005$) and peak speed in sprint (mean difference: 0.706 km/h; $p = 0.002$). No significant differences were found between groups regarding the observed improvements.

Discussion: In conclusion, this study suggests that the initial level of physical fitness significantly influences the magnitude of adaptations. Specifically, players with lower fitness levels appear to benefit more from training interventions. Improvements in CMJ and aerobic capacity in SSG seem to depend on players' fitness levels, and a similar trend is observed in HIIT for CMJ and peak speed. Individualizing training programs is recommended, with a focus on providing greater or different stimuli to more well-prepared players to ensure their continued development.

KEYWORDS

football, athletic performance, trainability, sports training, small-sided games

Introduction

Improving key physical fitness attributes in soccer players, such as muscle power, aerobic capacity, and linear sprinting ability, is crucial for meeting the demands of both training sessions and competitions (Buchheit et al., 2010). Muscle power is essential for explosive actions like shooting and jumping (Campo et al., 2009), as well as for generating the power needed for acceleration and changes in direction (Northeast et al., 2019). Additionally, maintaining high velocity and linear sprinting speed has become increasingly important in soccer matches due to the growing frequency of such movements (Reynolds et al., 2021). This enables players to holder rapid defensive or offensive transitions and overtake opponents in duels (Caldbeck and Dos'Santos, 2022). Lastly, a robust aerobic capacity supports sustained physical performance by enhancing endurance, allowing players to maintain high-intensity efforts throughout the match (Radziminski et al., 2020). Therefore, implementing effective training methods to improve these physical attributes can lead to better overall performance and increased match intensity.

In soccer, both small-sided games (SSGs) and running-based high-intensity interval training (HIIT) have been shown to effectively enhance aerobic capacity (Moran et al., 2019; Clemente et al., 2021c). SSGs also support improvements in muscle power and linear sprinting ability, though results in these areas are more diverse (Clemente et al., 2021b). SSGs replicate game dynamics by reducing the size of the pitch and the number of players, while adjusting rules to promote sport-specific adaptations (Hill-Haas et al., 2011; Bujalance-Moreno et al., 2019). This approach helps players engage in conditioning training while maintaining technical skills and tactical awareness (Ometto et al., 2018). Research indicates that SSGs are as effective as HIIT in significantly improving aerobic capacity (Clemente et al., 2023), though their impact on muscle power and sprint performance is less consistent (Faude et al., 2014; Los Arcos et al., 2015). In contrast, running-based HIIT consistently enhances aerobic capacity (Clemente et al., 2021c) and, in some forms, such as sprint interval training, also improves linear sprint performance (Hang et al., 2024).

A notable methodological gap in the current literature is the lack of consideration for players' initial fitness levels when analyzing adaptation outcomes (Clemente et al., 2021a). Additionally, there is limited understanding of how physical fitness levels influence the effectiveness of these training methods. For instance, the impact of SSGs may vary based on whether players have lower or higher fitness levels, with potential challenges in adapting the training to individual needs. This variability in stimulus and the complexity of individualizing SSGs (Clemente, 2020) raise questions about whether the effectiveness of these drills is constrained by players' fitness levels, especially for those who are already highly fit.

Given the limited research on how baseline physical fitness levels may influence the magnitude of adaptations when comparing SSGs and HIIT, further studies are needed to understand the impact of trainability on key fitness parameters such as aerobic capacity, muscle power, and linear sprint performance. Investigating this issue not only offers an innovative approach and contributes to the body of knowledge, but it also has practical implications for coaches. Such research could help coaches select the most effective training methods for individual players, thereby optimizing the training stimulus and improving overall performance. Based on this, this study purposed to compare the impacts of SSG and HIIT on male soccer players, while also considering the players' athleticism, categorized into lower and higher total athleticism scores (TSA).

Methods

We have reported this article in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for cohort studies.

Participants

Using convenience sampling, the following criteria were established to make players from both teams eligible for this study: (i) aged 16–18 years old (the latest stage of specialization); (ii) male; (iii) with more than 3 years of soccer experience; (iv) not injured during the observational period (6 weeks) or in the month prior to the start of the pre-season; (v) not participating in additional training sessions beyond those prescribed within the context of their soccer training; and (vi) being outfield players (i.e., excluding goalkeepers).

Following the initial assessment, each athlete's better CMJ, 30-m linear sprint and VIFT values were recorded. To standardize the scores for each measure, z-scores were computed based on the mean and standard deviation from the 43 players. The TSA for each athlete was derived from the sum of the z-scores across these measures (Turner et al., 2019). Players were categorized into two groups based on their TSA sum of z-scores: (i) those with a lower TSA if the z-score (non-fit) was below the median (−0.2), and (ii) those with a higher TSA (fit) if the z-score was above the median (−0.2). Furthermore, for data analysis, the difference between post-preseason and pre-preseason measurements was used as the final outcome for each measure, enabling comparisons between groups.

Players were recruited from two regional-level teams competing in the same age group and division. These teams were selected due to their convenience and because they adopted SSG and HIIT strategies in their training, as part of a consultancy provided by the researchers to the coaching staff. Out of the 51 players initially identified, 6 were excluded because they were goalkeepers and 2 were excluded due to injuries at the time of the first evaluation.

Before starting the study, we extended invitations to potential participants and provided them with comprehensive details about the study's design, procedures, associated risks, and anticipated benefits. Following this, both the participants and their legal guardians completed and signed an informed consent form. This form described their right to withdraw from the study at any point without facing any repercussions. The study received ethical clearance from the Institutional Ethical Review Board at the ChengDu Sports Univ, under the reference number 102/2024. The study was conducted in accordance with the ethical principles set forth in the Declaration of Helsinki.

Study design and setting

This study used a prospective cohort design, tracking two teams during a 6-week pre-season period. Evaluations were conducted at

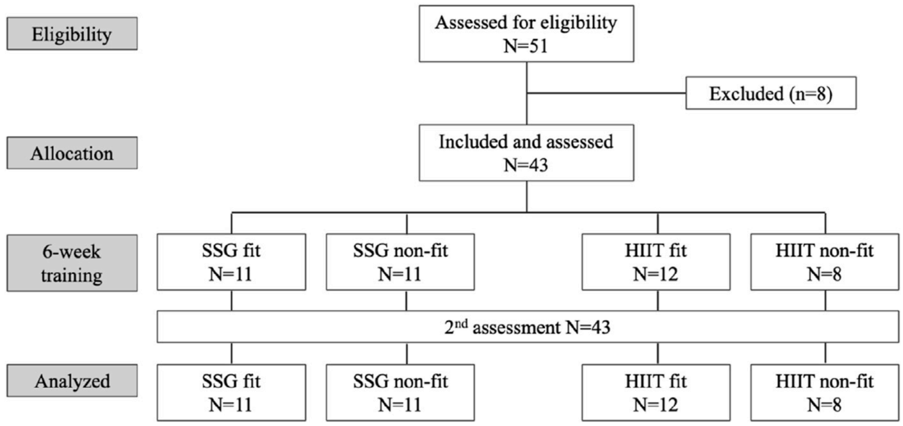

FIGURE 1
Participant Flow Chart. SSG: small-sided games; HIIT: high-intensity interval training.

the beginning and end of this period (pre-post analysis). Both teams employed SSG and HIIT strategies similarly within their groups. Consequently, half of the participants in each team were exposed to each type of training. The volume of training dedicated to each approach was consistent across the groups.

The study was conducted during the pre-season period. In the first week, players were evaluated to determine their baseline physical fitness levels. Over the subsequent 6 weeks, they participated in regular training sessions (4 times a week). During these sessions, half of the participants engaged in aerobic-based training twice a week, with one group doing SSG and the other group performing HIIT. At the end of the 6-week pre-season period, a second evaluation was conducted. All players were assessed at both time points, with no dropouts recorded (Figure 1).

SSG and HIIT training

This study investigated the potential effects of physical fitness levels on the magnitude of adaptations in players exposed to SSG and HIIT. SSG and HIIT were treated as independent variables for analysis. To ensure balance across playing positions and fitness levels, players were stratified by their roles (defenders, midfielders, and forwards). Within each positional category, a random assignment was conducted by using a coin toss, with the first toss determining the allocation for SSG and subsequent allocations alternating to ensure equal distribution. Coaches maintained these assignments consistently over the 6-week intervention period to avoid cross-training effects.

Players in the SSG group participated in two weekly sessions (separated by 48 h) of these drills, while players in the HIIT group followed a similar schedule on the same training days. Each session began with a dynamic warm-up, which included 7 min of jogging, 5 min of lower-limb stretching, and 5 min of neuromuscular exercises such as jumping and accelerations. Both SSG and HIIT sessions were part of the training dedicated to aerobic-based training.

It is important to note that the remaining sessions, focused on technical and tactical aspects, were planned and prescribed by the coaches without interference from the researchers. These sessions included one focused on strength and power and another on acceleration and linear speed. Table 1 details the aerobic training process for those exposed to SSG and HIIT.

Methodological procedures

In addition to the independent variables of SSG and HIIT, we also considered the baseline physical fitness level of the participants as another independent variable in our study. Using the Total Score Average (TSA), which is derived from the average Z-scores of the testing battery, we classified participants into two groups: those above the median were categorized as "fit," and those below the median were categorized as "non-fit." This classification aimed to assess the impact of fitness level on the magnitude of adaptations, with the goal of determining whether trainability influences the extent of these adaptations.

The testing battery included several assessments: the countermovement jump (CMJ), measured by jump height in centimeters; a 30-meter linear sprint, measured by completion time in seconds; and the 30–15 Intermittent Fitness Test (30–15 IFT), measured by the maximum speed attained in kilometers per hour. These assessments were classified as dependent variables and were compared before and after the 6 weeks of training exposure.

Physical fitness assessments

The evaluations were conducted under consistent conditions during both pre-season and post-pre-season analysis. On the first training session of the week, following 48 h of rest, players were assessed for muscle power, linear speed, and aerobic capacity. These assessments took place in the afternoon on synthetic turf, with temperatures averaging 24.6°C ± 1.2°C and relative humidity at 56.1% ± 2.3%. The team evaluators were the same in both moments.

The process began with the collection of demographic information (e.g., sex, birthdate), followed by anthropometric

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TABLE 1 Description of the training process for SSG and HIIT.

	SSG	HIIT
Week 1, training 1	Reps: 6 | Time per rep: 1 min | Time between rep: 3 min	Reps: 6 | Time per rep: 1 min | Time between rep: 3 min
	Format: 2v2 | Field: 20 × 15 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 90%VIFT | Running at straight line
Week 1, training 2	Reps: 6 | Time per rep: 1 min | Time between rep: 3 min	Reps: 6 | Time per rep: 1 min | Time between rep: 3 min
	Format: 2v2 | Field: 20 × 15 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 90%VIFT | Running at straight line
Week 2, training 3	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min
	Format: 2v2 | Field: 20 × 15 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 90%VIFT | Running at straight line
Week 2, training 4	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min
	Format: 2v2 | Field: 20 × 15 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 90%VIFT | Running at straight line
Week 3, training 5	Reps: 3 | Time per rep: 3 min | Time between rep: 3 min	Reps: 3 | Time per rep: 3 min | Time between rep: 3 min
	Format: 4v4 | Field: 30 × 25 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 85%VIFT | Running at straight line
Week 3, training 6	Reps: 3 | Time per rep: 3 min | Time between rep: 3 min	Reps: 3 | Time per rep: 3 min | Time between rep: 3 min
	Format: 4v4 | Field: 30 × 25 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 85%VIFT | Running at straight line
Week 4, training 7	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min
	Format: 4v4 | Field: 30 × 25 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 85%VIFT | Running at straight line
Week 4, training 8	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min
	Format: 4v4 | Field: 30 × 25 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 85%VIFT | Running at straight line
Week 5, training 9	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min
	Format: 2v2 | Field: 20 × 15 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 90%VIFT | Running at straight line
Week 5, training 10	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min
	Format: 4v4 | Field: 30 × 25 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 85%VIFT | Running at straight line
Week 6, training 11	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min	Reps: 8 | Time per rep: 1 min | Time between rep: 3 min
	Format: 2v2 | Field: 20 × 15 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 90%VIFT | Running at straight line
Week 6, training 12	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min	Reps: 4 | Time per rep: 3 min | Time between rep: 3 min
	Format: 4v4 | Field: 30 × 25 m | No goalkeeper | Mini-goals (2 × 1 m)	Intensity of running: 85%VIFT | Running at straight line

SSG: small-sided games; HIIT: high-intensity interval training; Reps: repetitions; VIFT: final velocity at 30–15 intermittent fitness test.

assessments (standing height and body mass). This was followed by a standardized warm-up, which included 7 min of jogging, 5 min of lower limb dynamic stretching, and 5 min of jumping and acceleration drills. After a 3-minute rest, the evaluations began, starting with the CMJ test, followed by the linear speed test, and concluding with the 30–15IFT. Players were allowed 5 min of rest between tests, and hydration was permitted during these intervals.

Countermovement jump test

To evaluate the vertical jump height of athletes, the CMJ technique was utilized. Participants started from a standing position with their hands resting on their hips. They then performed a quick bending motion at the knees and hips, followed by an explosive upward extension of their lower body to achieve the jump. Jump height was recorded with the MyJump 2 app (version 1.0.8, Xiaomi 11i, China), known for its strong validity compared to gold-standard techniques like force plates and its established reliability (Haynes et al., 2019; Haynes et al., 2019). Each participant first completed a familiarization attempt before undertaking two jump trials, with a 1 min rest period between each. The coefficient of variation for the variability between trials was 2.8%. For subsequent data analysis, the highest jump recorded from the two attempts (measured in centimeters) was selected.

30-m linear sprint test

To assess linear sprint performance, a 30-meter linear sprint test was performed on synthetic turf. Participants began their sprint from a split stance, with their dominant leg positioned forward. They started their run 30 cm before the initial photocells set, ensuring they maintained the same starting position and front leg throughout the test.

A countdown in seconds signaled the start of the sprint. Three pairs of photocells were positioned at the players' hip height: at the starting line, at the 25-meter split, and at the finish line (30 m). Each

TABLE 2 Descriptive statistics (mean ± standard deviation) of the participants at baseline and post-preseason, separated by training group (SSG vs HIIT) and TSA classification (fit vs non-fit).

	SSG fit (N = 11)	SSG non-fit (N = 11)	HIIT fit (N = 12)	HIIT non-fit (N = 8)
Baseline				
CMJ (cm)	34.8 ± 3.8	29.6 ± 3.6#	34.8 ± 3.2	29.1 ± 3.3#
30-m sprint peak speed (km/h)	28.7 ± 2.2#	28.4 ± 1.7#	28.8 ± 1.1#	27.4 ± 0.6#
VIFT (km/h)	17.1 ± 0.6#	15.9 ± 0.7#	16.5 ± 0.7#	15.8 ± 0.9#
Post pre-season				
CMJ (cm)	35.2 ± 3.2	33.0 ± 3.0#	35.3 ± 2.1	32.1 ± 2.8#
p-value and d-value (within-group)	$p = 0.366$; d = 0.114	$p < 0.001$; d = 1.030	$p = 0.197$; d = 0.189	$p < 0.001$; d = 0.984
30-m sprint peak speed (km/h)	29.0 ± 1.8#	28.9 ± 1.5#	29.1 ± 0.9#	28.4 ± 0.7#
p-value and d-value (within-group)	$p = 0.031$; d = 0.150	$p < 0.001$; d = 0.313	$p = 0.018$; d = 0.300	$p < 0.001$; d = 1.538
VIFT (km/h)	17.5 ± 0.5#	17.0 ± 0.3#	17.2 ± 0.5#	16.9 ± 0.4#
p-value and d-value (within-group)	$p = 0.007$; d = 0.727	$p < 0.001$; d = 2.200	$p < 0.001$; d = 1.167	$p < 0.001$; d = 1.692

CMJ, countermovement jump; VIFT, final velocity in the 30–15 intermittent fitness test, TSA, total score of athleticism. Statistically significant differences between pre- and post-season values are marked (#) at $p < 0.05$.

participant completed two 30-meter sprints with a 3-minute rest period between attempts. Peak speed was estimated by dividing the time taken to cover the final 5 m (between 25 and 30 m) by the duration of that split. A previous study (Zabaloy et al., 2021) have recommended this approach and found it to have nearly perfect correlations with radar gun measurements. The variability in sprint times within each participant, measured as a coefficient of variation, was 2.4%. For further analysis, the fastest of the two sprint (measured in km/h) was used.

30–15 intermittent fitness test

To evaluate players' capacity for sustained intermittent exercise, the 30–15 IFT was used (Buchheit, 2008). This test involves performing a series of shuttle runs, each lasting 30 s, followed by a 15-second period of passive recovery. The pace of the runs was controlled by audio beeps, with the initial speed set at 8 km/h and increasing by 0.5 km/h every 30 s.

The test continued until the participant either could no longer keep up with the increasing pace or chose to stop due to exhaustion. The final result was recorded as the highest speed achieved during a completed 30-second interval, representing the final velocity in the 30–15 IFT (VIFT), measured in kilometers per hour (Buchheit, 2008).

Study size

The calculation for the sample size was informed by the mean values reported in a previous comparison study of SSG versus HIIT (Nayıroğlu et al., 2022). Using G*Power (version 3.1.9.6, Heinrich-Heine-Universität Düsseldorf, Düsseldorf, Germany), which is designed for repeated measures across factors, the analysis considered four groups and two measurement points. With a significance level (alpha) set at 0.05 and a desired power of 0.85, the required sample size was determined to be 44 participants.

Statistical procedures

In the results section, we provided descriptive statistics including means, and standard deviations. After verifying data normality and homogeneity with the Kolmogorov-Smirnov test ($p > 0.05$) and Levene's test ($p > 0.05$), we proceeded to inferential statistical analysis. A mixed ANOVA testing interactions between time, group and fit category was conducted. A two-way ANOVA was used to compare results both groups (SSG and HIIT) and fit category (fit and non-fit). Effect sizes for the ANOVA were quantified using partial eta squared (partial η^2), with interpretations classified as follows: values greater than 0.01 indicated a small effect, values over 0.06 signified a moderate effect, and those above 0.14 represented a large effect (Richardson, 2011). Post hoc comparisons were performed using Bonferroni adjustments. Additionally, Cohen's d effect size was used to determine pairwise comparisons, with the following classifications (Hopkins et al., 2009): 0.0–0.2 indicating a trivial effect size, 0.2–0.6 a small effect size, 0.6–1.2 a moderate effect size, 1.2–2.0 a large effect size, and values greater than 2.0 representing a very large effect size. All statistical procedures, including descriptive statistics, Kolmogorov-Smirnov and Levene's tests, mixed repeated measures ANOVA, partial eta squared calculations, and Bonferroni tests, were executed with SPSS software (version 29.0.0, IBM SPSS Statistics, Armonk, NY: IBM Corp), and significance was set at $p < 0.05$. The graphical illustrations were conducted in JASP software (version 0.19.0, University of Amsterdam, The Netherlands).

Results

This study included 43 male soccer players with an average age of 16.5 ± 0.7 years, a body mass of 65.1 ± 6.0 kg, and a height of

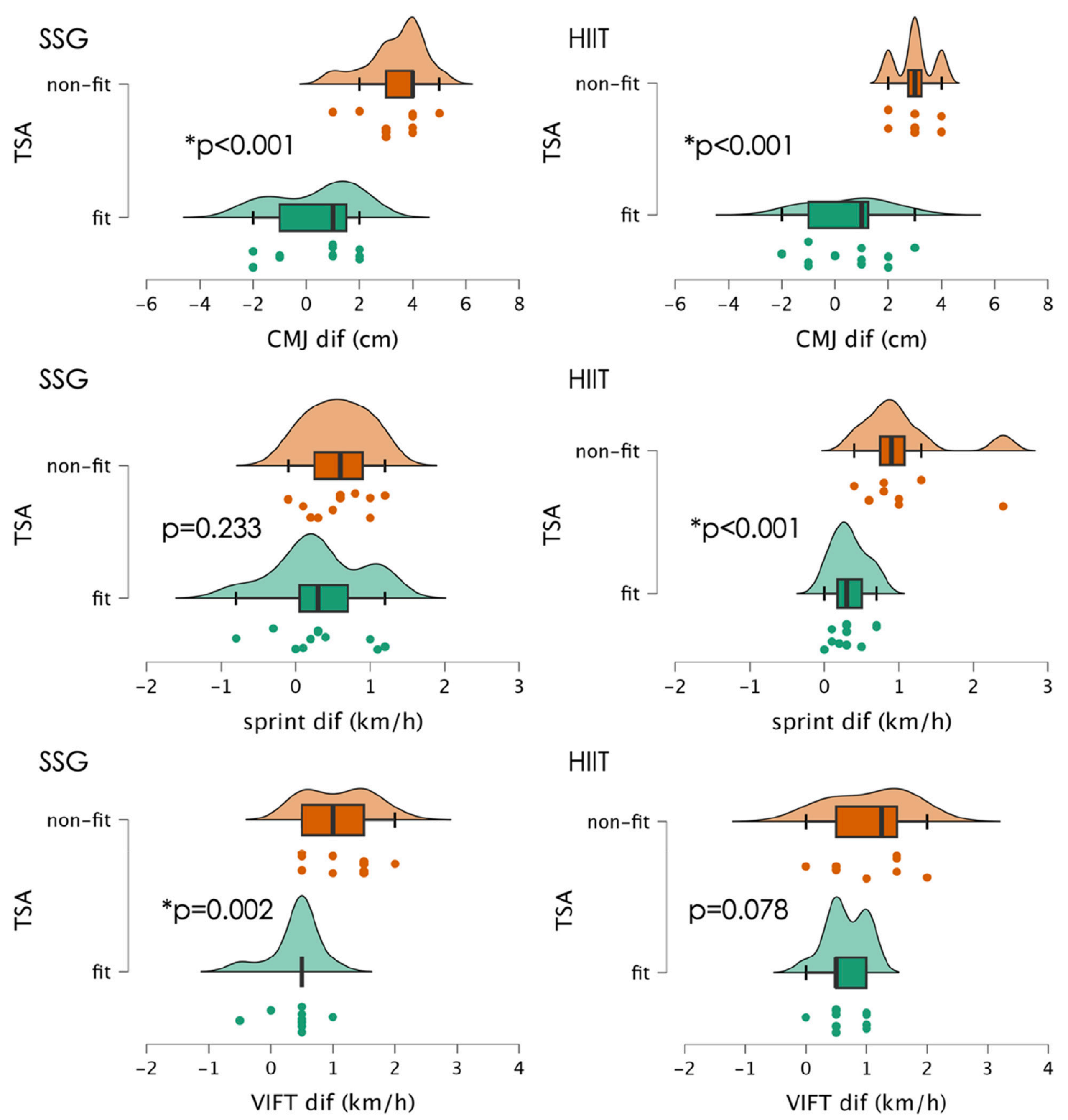

FIGURE 2
Descriptive statistics of changes in countermovement jump (CMJ), 30-meter linear sprint peak speed, and 30–15 intermittent fitness test (VIFT) between pre- and post-season assessments, categorized by training method (SSG and HIIT) and fitness group (fit vs non-fit). Error bars represent standard deviations. Asterisks (*) indicate significant differences within each group comparing fit and non-fit players ($p < 0.05$). SSG: small-sided games; HIIT: high-intensity interval training.

176.2 ± 5.3 cm, and an average of 5.2 ± 1.1 years of experience. Table 2 presents the descriptive statistics of the participants at both evaluation points, organized by groups and TSA classification.

No significant interactions between time, group, and TSA classification were observed for CMJ ($F = 0.368$; $p = 0.547$; partial $\eta^2 = 0.010$), peak speed in sprint ($F = 2.368$; $p = 0.132$; partial $\eta^2 = 0.059$), and VIFT ($F = 0.915$; $p = 0.345$; partial $\eta^2 = 0.024$).

SSG non-fit participants showed a significant improvement in CMJ performance, with a mean difference of 3.4 cm ($p < 0.001$; d = 1.030, moderate effect size). Similarly, HIIT non-fit participants exhibited a significant enhancement, with a mean difference of 3.0 cm ($p < 0.001$; d = 0.984, moderate effect size). In contrast, no significant changes were observed in CMJ performance for SSG fit ($p = 0.366$; d = 0.114, trivial effect size) and HIIT fit ($p = 0.197$; d = 0.189, trivial effect size) when comparing post-intervention to pre-intervention measurements.

SSG non-fit participants showed a significant improvement in line sprint peak speed performance ($p < 0.001$; d = 0.313, small effect size), as well as fit players ($p = 0.031$; d = 0.150, trivial effect size). Similarly, HIIT non-fit participants showed significantly peak speed enhancement ($p < 0.001$; d = 1.538, large effect size), as well as fit players ($p = 0.018$; d = 0.300, small effect size). Finally, SSG non-fit participants showed a significant improvement in VIFT performance ($p < 0.001$; d = 2.200, very large effect size), as well as fit players ($p = 0.007$; d = 0.727, moderate effect size). Similarly, HIIT non-fit participants showed significantly VIFT enhancement ($p < 0.001$; d = 1.692, large effect size), as well as fit players ($p < 0.001$; d = 1.167, moderate effect size).

The Figure 2 presents the descriptive statistics of the delta variations (post-pre) for CMJ, linear sprint, and VIFT in SSG and HIIT. Non-fit players showed significantly greater CMJ improvements in SSG compared to fit players (mean difference: 3.0 cm; $p < 0.005$; d = 2.233, very large effect size). A similar trend was observed in the HIIT group, with non-fit players also demonstrating greater improvements than fit players (mean difference: 2.5 cm; $p < 0.005$; d = 2.209, very large effect size). No significant differences in CMJ improvements were observed between groups for both non-fit ($p = 0.556$; d = 0.388, small effect size) and fit players ($p = 0.806$; d = 0.089, trivial effect size).

Non-fit players showed significantly greater peak speed in sprint improvements in HIT compared to fit players (mean difference: 0.706 km/h; $p = 0.002$; d = 1.677, large effect size). However, no significant differences between fit and non-fit players were observed in SSG group ($p = 0.233$; d = 0.481, small effect size). Significant differences in peak speed in sprint improvements were observed between groups in the case of non-fit (SSG: 0.564 km/h vs HIIT: 1.037 km/h; $p = 0.038$; d = 0.923, moderate effect size), although no significant differences were found in fit players ($p = 0.939$; d = 0.045, trivial effect size).

Non-fit players showed significantly greater VIFT improvements in SSG compared to fit players (mean difference: 0.682 km/h; $p = 0.002$; d = 1.491, large effect size), although no significant differences were found in HIIT group ($p = 0.078$; d = 0.789, moderate effect size). No significant differences in VIFT improvements were observed between groups for both fit ($p = 0.205$; d = 0.735, moderate effect size) and non-fit players ($p = 0.899$; d = 0.047, trivial effect size).

Discussion

Our study highlighted several key findings: initial fitness level and trainability significantly influence the extent of improvement. Non-fit players exhibited significantly greater improvements in CMJ, regardless of whether they participated in SSG or HIIT. They also showed enhanced peak speed in linear sprints, particularly with HIIT, and improved aerobic capacity (measured by VIFT), especially with SSG. Despite the repeated measures results indicates that both fit and non-fit players exhibit tendencies for significant within-group improvements, the study suggests that the level of initial fitness constrains the magnitude of adaptation. These findings offer valuable insights for the coaching community, emphasizing that adjustments to training stimuli may be necessary to ensure appropriate adaptations based on players' trainability.

Our results showed that CMJ improvements were significant only in non-fit players, who experienced substantial gains from both SSG and HIIT, with no significant difference between the two training methods. It appears that the players' initial fitness level played a more crucial role in determining the extent of improvement. Fit players, to start with, did not show any significant changes after the 6-week period, indicating that initial fitness level was a key factor in constraining the improvements. These results may help explain the often contradictory findings regarding CMJ adaptations following SSG and HIIT interventions. Some studies report significant improvements from these training approaches (Arslan et al., 2020), while others do not (Faude et al., 2014; Jastrzebski et al., 2014). Our findings suggest that the varying initial fitness levels of participants could be a key factor contributing to these differing outcomes.

The observed difference in CMJ improvements between fit and non-fit players can be explained, possibly, through the concept of a fitness ceiling (Díaz-Serradilla et al., 2023). Non-fit players exhibited significant CMJ gains from both training methods, likely due to their greater potential for adaptation in response to novel or intensified stimuli. This is consistent with the principle of progressive overload, where individuals with lower baseline fitness levels experience more substantial improvements from training as they are further from their physiological limits (Morgans et al., 2014). Conversely, fit players, who are closer to their peak physical capacity, showed insignificant changes, suggesting that their training-induced adaptations may be constrained by their existing fitness ceiling. Furthermore, the absence of a consistent and individualized neuromuscular stimulus that effectively targets neural drive, muscle force, and power may also explain the lack of improvements in this group of players (Querido and Clemente, 2020).

Our results also showed that peak sprint speed improved significantly more in non-fit players compared to fit players, but only in the HIIT group. In contrast, there were no significant differences in sprint speed between fit and non-fit players in the SSG group. Additionally, non-fit players who underwent HIIT experienced significantly greater improvements than those who participated in SSG. Our results are consistent with a study (Silva et al., 2022) that exclusively examined SSG and found no effect of baseline fitness levels on peak speed adaptations. Additionally, our study partially aligns with research suggesting that HIIT offers some advantages over SSG for enhancing sprint performance (Stojiljković et al., 2019).

Our results suggest that HIIT, even at sub-maximal speeds, although intense, as observed in our study, leads to greater adaptations, especially in individuals with lower baseline fitness levels. HIIT appears to drive more substantial neuromuscular adaptations and improvements in muscle strain and anaerobic capacity (Buchheit and Laursen, 2013), which may be more pronounced in less fit individuals who have a higher potential for improvement. In contrast, SSG, conducted in limited spaces due to the implemented formats, may not have exposed players to sufficiently high speed intensities (Castagna et al., 2017). As a result, SSG might be less effective at inducing maximal speed adaptations, regardless of baseline fitness.

The aerobic performance measured using the 30–15IFT indicated that non-fit players in the SSG group benefited significantly more than fit players. However, no significant differences between fit and non-fit players were observed in the improvements in HIIT group. No differences in the effects between the training methods was observed. Our results contrast with a previous study on SSG, which found no improvement differences between players with higher and lower TSA (Silva et al., 2022). However, our findings regarding improvements in both SSG and HIIT are consistent with recent evidence suggesting that both methods have similar beneficial effects on aerobic performance in soccer players (Clemente et al., 2023).

Non-fit players in the SSG group exhibited greater improvements compared to their fit counterparts, potentially due to the SSG's capacity to enhance aerobic conditioning through environmental based scenarios that may be more challenging for those with lower baseline fitness. This could be attributed to increased game and tactical engagement, which may lead to more significant physiological adaptations in less fit players, thereby enhancing the training load factors that influence these adaptations (Teixeira et al., 2022; Teixeira et al., 2023). On the other hand, in those with higher fitness level, maybe the heterogeneous of the stimulus may celling the magnitude of effects (Hill-Haas et al., 2008). Conversely, the lack of different improvement between fit and non-fit players in the HIIT group points to the method's generalized efficacy in enhancing aerobic capacity across fitness levels, individualizing the stimulus (Buchheit, 2008).

Despite the valuable insights provided by this study, several limitations should be considered. Several limitations should be considered. First, the short intervention duration (6 weeks) may not adequately reflect the long-term adaptations typically associated with SSG and HIIT. Extending the intervention could provide insights into cumulative or plateau effects that may arise over an extended training period. Additionally, conducting the study during pre-season may limit its applicability to other competitive phases, where training load and intensity differ. Furthermore, the study did not measure individual physiological responses to training stimuli, such as heart rate variability or neuromuscular adaptations, which might explain the limited response in highly trained (fit) players. In this regard, incorporating training load (Paiva et al., 2023; Teixeira et al., 2024) information and creating a modulation of adaptations based on it could be valuable in future studies. Additionally, investigating the effects of individualized training programs that consider baseline fitness levels could offer further insights into optimizing training for soccer players. F.

This study reveals the importance of adjusting training programs to players' initial fitness levels to maximize performance gains. For coaches, the key takeaway is the necessity of individualizing training stimuli to address the specific needs of both fit and non-fit players. Non-fit players may benefit from the varied stimuli provided by both SSG and HIIT, as they have greater potential for improvement and adaptation. Conversely, fit players might require more targeted interventions to achieve further gains, given their proximity to physiological limits. Coaches may consider implementing targeted training interventions based on fitness level, with specific focus areas for fit and non-fit players. For non-fit players, SSG and HIIT can both serve as effective tools for improving explosive strength, aerobic capacity, and speed, as these athletes may respond more readily to basic conditioning stimuli. Conversely, fit players may require more tailored approaches, such as progressive overload or varied neuromuscular stimuli, to exceed existing fitness thresholds and prevent plateaus. Including regular assessments and adjusting training loads throughout the season could maximize performance gains.

Conclusion

In conclusion, our study highlights the role of initial fitness levels and trainability in determining the effectiveness of training interventions on performance improvements. Non-fit players exhibited substantial gains across CMJ, peak sprint speed, and aerobic capacity, particularly benefiting from both SSG and HIIT. This suggests that lower baseline fitness is associated with greater potential for adaptation and improvement from diverse training stimuli. Conversely, fit players exhibited limited changes, primarily due to their proximity to physiological ceilings which constrain further gains. These findings highlight the necessity for coaches to tailor training programs based on players' fitness levels, incorporating individualized approaches to maximize adaptations and performance outcomes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by The study received ethical clearance from the Institutional Ethical Review Board at the ChengDu Sports Univ, under the reference number 102/2024. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants'; legal guardians/next of kin.

Author contributions

LW: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Validation, Writing–original draft, Writing–review and editing. YZ: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Supervision, Validation, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Response of infrared thermography related parameters to (non-)sport specific exercise and relationship with internal load parameters in individual and team sport athletes—a systematic review

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Introduction: Monitoring internal load is crucial for athletes but often requires invasive methods for muscle-related parameters, limiting practicality. Infrared thermography (IRT) related parameters might overcome this limitation. This systematic review aimed to examine the available literature on the response of IRT related parameters to (non-)sport specific exercise and reveal relationships with internal load parameters in athletic populations.
Methods: Four scientific databases were systematically searched (February 2024) with keywords related to IRT, load, and sports disciplines. Risk of bias was evaluated using QUADAS-2. Main inclusion criteria for studies were i) reporting of IRT related parameters and other internal load parameters prior/post (non-) sport specific exercise ii) inclusion of least Tier 2 athletes ≥ 18 years. After identifying n = 10,538 studies, 13 articles (n = 231 participants) were included.
Results: Following (non-)sport specific exercise in athletic populations, the majority of relevant studies showed a decrease in IRT related parameters within 15 min, while studies showed an increase in IRT related parameters following 30 min, 24 h, 48 h, and 72 h after exercise cessation. Relationships between alterations in IRT related parameters and other internal load parameters are inconsistent across the literature.
Conclusion: While the majority of studies show an increase in IRT related parameters following (non-)sport specific exercise, relationships with other internal load parameters and underlying physiological mechanisms evoking IRT related alterations are not conclusively revealed in athletic populations. Future research needs to assess the relationship of IRT related parameters especially with inflammatory parameters in athletic populations following (non-)sport specific exercise. Practitioners might assess IRT related parameters in conjunction with other load parameters.

KEYWORDS

individualization, precision training, muscle, inflammation, signature

1 Introduction

Quantifying internal load by monitoring of various parameters holds a key role to individualize training procedures to advert fatigue, mitigate the risk of illness and injury, and optimizing performance outcomes (1). In this context, internal load pertains to an individual's psychophysiological response to the external load, which can be defined as the executed mechanical work (1). Depending on the bodily system at question, different methodologies are available to practitioners to assess internal load of athletes (2–4). However, these methodologies are often intrusive and/or time-consuming, particularly when muscle related parameters should be evaluated (4, 5). This limits the assessment of muscle related parameters in practice. Consequently, other approaches are needed which overcome these limitations.

To assess muscle related parameters, non-invasive infrared thermography (IRT) following exercise (6) is increasingly used in athletic populations (7–10) as well as in the medical literature (8, 11). IRT is a non-radiating, contact-free, and non-invasive approach to measure skin temperature and derive different parameters (e.g., skin temperature asymmetries, changes in skin temperature) (12). While healthy subjects are anticipated to maintain thermal equilibrium under neutral conditions (13), the metabolic, biomechanical, and physiological demands associated with training and competitive activities may elicit fluctuations in skin temperature after exercise cessation (12). The underlying mechanisms of the change of body surface radiation during and after exercise relies on several muscular and physiological factors, including increased ATP-production, neuronal responses, vasomotor adjustments and inflammatory processes (14–18). The specifics of these mechanisms, including their dependence on exercise type, are eloquently explained elsewhere (14, 17, 18).

Given the link between IRT and physiological mechanisms, research explored whether changes in skin temperature are associated with physiological parameters. Studies indicated that IRT-related parameters correlate with performance metrics, such as maximal oxygen uptake and heart rate (19, 20). Information about skin temperature alterations following exercise has been used to detect skeletal muscle overload and fatigue in athletic populations (21). Additionally, it was shown that if IRT related parameters are used to identify players at potential risk, injuries could be reduced in elite soccer players (21, 22).

However, despite isolated studies, there is no systematic review available in the literature on the response of IRT related parameters in response to (non-)sport specific exercise. To provide a stronger evidence base to inform sports practice and future research, the aim of this article was to systematically review available literature on the response of IRT related parameters to (non-)sport specific exercise and relationship with internal load parameter.

2 Methods

2.1 Study design

To be considered for inclusion, IRT related parameters must have been calculated from infrared thermographic images and must have been captured either pre and post, or only post (non-) sport specific exercise or competition in compliance to the Glamorgan Protocol (2) and/or the contemporary consensus statement recommendations delineated by Thermographic Imaging in Sports and Exercise Medicine (TISEM) for the measurement of human skin temperature (23). Studies were excluded if they did not align with these scientific recommendations.

Studies that assessed IRT related parameters preceding or concurrently with exercise, which involved consciously or unconsciously manipulated experimental conditions (e.g., environmental temperature), or which assessed methodological differences while obtaining IRT related parameters were out of the scope of this article and therefore excluded. Investigations where training was coupled with a manipulating experimental intervention (e.g., use of ergogenic aids, assessment of recovery procedures) were excluded.

2.2 Study populations

All investigations involving adult, healthy, able-bodied trained/developmental (at least Tier 2) team sport or individual sport athletes (24), regardless of sex or gender were included. As age is considered an influencing factor on thermographic parameters (25), and it has been demonstrated that skin temperature stabilizes after puberty (26), this review focuses on investigations incorporating athletes with a mean age of ≥18 years. Research involving non-human participants or participants with a mean age below 18 years was excluded. Studies with injured team sport players which are e.g., in the return to sport or return to play procedures were excluded.

2.3 Outcomes

In order to be included, the study must have examined IRT related parameters following (non-) sport specific exercise and the relationship between IRT related parameters (e.g., skin temperature; surface radiation temperature; skin temperature asymmetries) and at least one other internal load parameter in either the time, frequency or concentration domain (e.g., heart rate, ratings of perceived exertion, lactate). Accordingly, studies that measured skin temperature but did not integrate IRT-related parameters and/or internal load parameters were excluded.

2.4 Publication status and language

Only full-length original articles published in English in peer-reviewed journals will be considered, omitting "grey" literature such as conference abstracts, dissertations, theses, or reports. In addition, the reference lists of articles initially included were examined for additional publications of potential relevance. Articles published in other languages were excluded.

2.5 Search strategy

In accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (27) and the PRISMA 2020 Checklist (Supplementary Table S1), we conducted a systematic search of Ovid MEDLINE In-Process and Other Non-Indexed Citations, CINAHL, EMBASE, and Web of Science (with no restrictions on publication date) in February 2024 to identify potentially relevant articles using the search criteria outlined in Supplementary Table S2. The development of search terms and medical subject headings (MeSH) was conducted in collaboration with a skilled librarian. In addition, reference lists of identified articles were screened to detect pertinent articles that might have been failed to notice using this search profile.

2.6 Selection of articles

After importing potentially relevant articles into Citavi 6 (QSR International, Burlington, MA, USA) and removing duplicates, one of the authors screened the titles and abstracts based on our inclusion criteria, while a second investigator independently validated those evaluations. Subsequently, both individuals thoroughly reviewed the full texts of the relevant articles to assess eligibility (with awareness of the journals and authors involved). Discrepancies were resolved through discussion between authors, until a consensus was reached.

2.7 Data extraction and analysis

As previously performed (28), the process of data extraction from each article identified was divided into the following steps: (1) study characteristics by the publication details (authors, journal, date), sports, participants (mean age, number, sex), level of performance; (2) study-defined training or competition characteristics, data and time point related to internal load parameters; (3) data and time points related to thermographic parameters, analyzed body region of the thermographic assessment; (4) methodological approaches of the thermographic analysis by extracting the camera type, methodological analysis method of thermographic parameters; (5) statistical analysis.

2.8 Data synthesis

To evaluate the magnitude of the effects as performed in previously published research (29), percentage changes ($\Delta\%$) were calculated and illustrated in Figure 2, Tables 3 and 4 for study outcomes using the following equation:

$$\Delta\% = \frac{(\text{Mpost} - \text{Mpre})}{\text{Mpre}} \times 100$$

Mpost represents the mean value after (long-term) training or competition and Mpre the baseline mean value.

Depicted mean values were calculated to summarize results of studies using standard equation, as follows:

$$\text{Mean value} = \frac{\sum \text{values}}{\text{number of values}}$$

2.9 Assessment of methodological quality

As recommended by Whiting et al. (30) and employed in similar research (11, 31), two experienced raters independently assessed the methodological quality using the QUADAS-2 scale, which comprises two domains: risk of bias and applicability (30, 32). The risk of bias domain evaluates items such as “patient or sample selection”, “index test”, “reference standard”, and “flow and timing”. The applicability domain assesses parameters including “sample selection”, “index test”, and “reference standard”. Regarding phase two of QUADAS-2, we tailored our review by omitting signal questions pertaining to blinding, as recommended in the official background document for objective index tests (30). Informed by fundamental principles, research, and recommendations (30, 32), we incorporated an additional signal question concerning patient/sample selection: “Does the study delineate inclusion and exclusion criteria for the selection process?”. Appropriate criteria were derived from Fernandez-Cuevas et al., 2015 (25) and involve medical history (injury, diseases, operations), intake factors (drug treatment, medicaments, alcohol, tobacco, stimulants) and application factors (ointments, cosmetics, therapies). Disagreements between raters were resolved through consensus.

3 Results

3.1 Study characteristics

The compilation of records identified and examined is illustrated in Figure 1. A total of $n = 10{,}538$ studies were identified (PubMed $n = 8{,}254$; EMBASE $n = 826$, CINAHL $n = 970$, Web of Science $n = 488$). 13 articles conformed to our inclusion criteria, including 231 participants (193 males, 28 females; 10 non-disclosed participants; Age range: 18 to 41 years). Ten of 13 studies included $n = 188$ tier 3 athletes (3, 4, 7, 9, 12, 33–37) and three included $n = 43$ tier 2 athletes (38–40).

Eleven (7, 9, 12, 33–40) of 13 studies were published in between 2019 and 2024. Six studies were conducted in soccer (3, 4, 9, 12, 33, 36), three in endurance sports such as half-marathon (38),

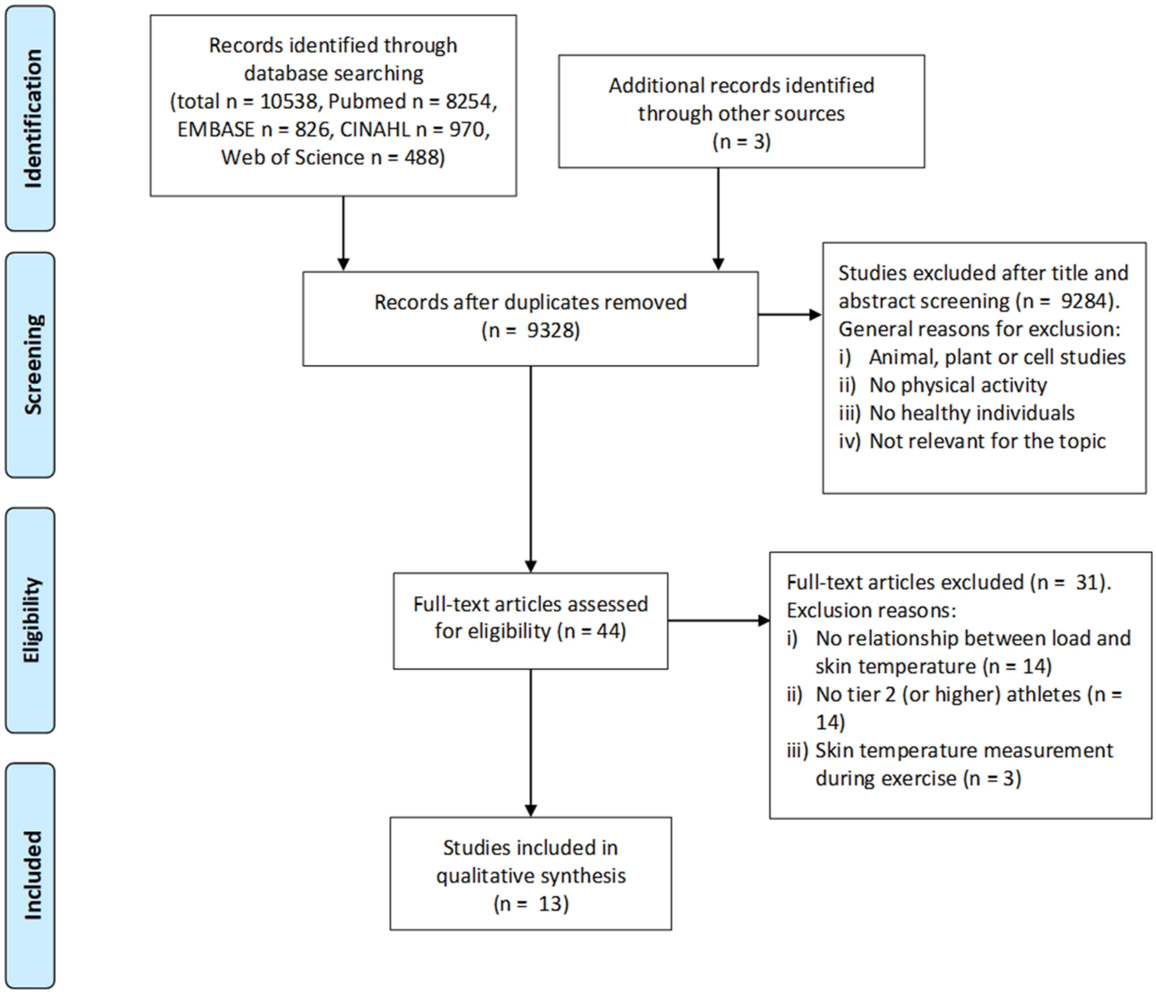

FIGURE 1
Process of study selection, from initial identification as potentially relevant to inclusion.

marathon (39), triathlon (40), two in judo (7, 37), one in sprinting (34) and one examined sprinters and endurance athletes (triathletes and long-distance runners) (35).

Tables 1, 2 summarize study characteristics including e.g., training or competition characteristics, load parameter description and methodological approaches.

Due to the variability in intervention periods and thereby methodological approaches (resulting in e.g., different statistics), studies were categorized based on the intervention time: (i) studies which conducted a single exercise, training session or investigating response to ≤ 3 soccer games ($n = 9$) (3, 4, 7, 33, 35, 37–40) and (ii) studies which encompassed frequent assessment of parameters across (at least parts of) a competitive season ($n = 4$) (9, 12, 34, 36).

3.2 Methodological approaches of infrared thermography

Regions of interest (ROIs) for IRT assessment included lower limbs only ($n = 9$) (3, 4, 9, 12, 33–36, 39), whole body ($n = 3$) (7, 37, 38), upper and lower limbs ($n = 1$) (40). The most assessed IRT related parameter was the mean skin temperature of different regions of interest (ROIs) [$n = 7$ (4, 7, 33, 37–40);]. Seven out of 13 studies analyzed differences in IRT related parameter between pre and post exercise and three studies investigated temperature asymmetries of contralateral ROIs (9, 12, 36). One study investigated daily IRT related parameter changes (34), while two studies conducted no further analysis (3, 35). Evaluation of IRT related parameters includes thermal pixelgraphy method ($n = 1$) (33), hot zone IRT related parameter percentage method ($n = 1$) (36) or averaging temperatures of the whole body by employing established equations ($n = 3$) (7, 37, 38). Additionally, one study investigated the relationship between load parameters and the post-training skin thermal patterns of the athletes (7). Carvalho et al. (9) used a cut-off value of 1°C difference in Tsk between contralateral limbs and the report of pain in one body region for further analysis. Majano et al. (12) grouped participants depending on thermal asymmetry in contralateral ROI of players with thresholds set at < 0.3°C for low asymmetry and ≥ 0.3°C for high asymmetry. Rodriguez Junior et al. (36) grouped participants according to their total distance traveled in half.

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TABLE 1 Characterization of the studies analyzed.

Sport	Article	N (male, female)	Age (years)	Level of performance	Study-defined training/competition characteristics	Load parameters	Time point of internal load measurement
Studies investigating response to a (partial) season; Soccer	(9)	22 (22,0)	27.7 ± 3.93	National C series championship	19 matches and 19 weeks with an interval of 7 days between matches	Blood creatine kinase concentration, athlete's perception of recovery, fatigue and pain	Post: 48 h
	(36)	20 (20,0)	Group 1: 25.6 ± 4.0; above total distance median Group 2: 27.7 ± 4.1; below total distance median	First Brazilian National Soccer League	Competitive season (16 weeks)	Blood concentration of creatine kinase, C-reactive protein, cortisol (no relationship/correlation calculated), rate of force development, impulse, peak force	Pre: Season Post: Season after an interval of 72-h of inactivity (no training)
	(12)	30 (30,0)	25.37 ± 3.60	Spanish second football division	12-week competitive period, training (five times/week) and match-play (one time/week)	Well-being questionnaire with following variables: (1) Modified version of Borg Rating of Perceived Exertion (RPE) (2) Stress (3) Rest time (4) Rest quality (5) Muscle Soreness	Pre: before training/competition (detailed time point n. r.)
Studies investigating response to a (partial) season; Other sports, Sprinting, Taper period	(34)	17 (9,8)	Male: 26.1 ± 3.3 Female: 25.1 ± 2.7	Elite; Polish National Team	10 d period consists of: Resistance training, speed-power training, speed-power training—relay runs, speed intervals, speed-power training (block starts), endurance training	Blood creatine kinase concentration	08:00 and 09:00 and between 20:00 and 21:00 local time; approximately Pre: 1 h, Post: not derivable
Soccer; Studies investigating response to ≤3 soccer games	(3)	1 (1,0)	27	First Division Brazilian Soccer League	Full official match	Blood/Plasma creatine kinase concentration	Pre: 24 h Post: 24 h, 48 h
	(4)	10 (n.r.)	19.00 ± 1.00	U-20 Brazilian first division soccer league	Two soccer matches with three days of recovery between each match	Blood/Plasma creatine kinase concentration	Pre: 24 h Post: 1st match: 24 h, 48 h Post: 2nd match: 24 h, 48 h
	(33)	11 (11,0)	29.26 ± 4.52	Elite team in brazilian soccer	Three consecutive games	Blood C-reactive protein concentration	Pre: 5 days Post: 24 h, 48 h, 72 h
Combat/Judo	(37)	23 (23,0)	20.1 ± 4.7	National team of college judo athletes, black belt	(a) The test started with 2 ukes (judoka threw) separated by 10 m and a tori (thrower judoka) between them; (b) the test begins at a speed 6 km/h where the tori must move alternately by the ukes and throw them by ippon-seoi-nage; (c) the stages were standardized in 2 min by 1-min interval; (d) each complete stage added to 0.5 km·h21 in the velocity; (e) the test finishes when the judoka cannot maintain the pace set by the current stage; and (f) accounts to total score using only the complete stages	Blood lactate concentration	Pre: 0 min Post: 5 min, 10 min, 15 min
	(7)	32 (25,7)	18.0 ± 3.5	Black-belt judokas from the Spanish junior national team	(a) Warm-up (20 min): 5-min running at low-intensity index <9 in 6–20 Borg scale, 5-min stretching, 5-min sprint interval training all-out (10″ with 10″ of interval), 4-min judo falling simulation (ukemis), and 1-min interval. (b) Technical training (30 min): 10-min technique application (uchi-komi) all-out = 8 × (20″ with 10″ of interval), 2-min interval and 8 × (20″ with 10″ of interval), 10-min throw technique (nage-komi), and 2 × 4-min handgrip dispute (2-min interval). (c) Combat training (Randori—40 min): standing combat (tachi-waza) 7 × 4-min with 1-min interval and 1 × 5-min (change the opponent every combat)	Blood: Count of white blood cells (leukocytes), subsets (neutrophils, lymphocytes, monocytes, eosinophils, basophils, and platelets), and haematocrit amount	Pre: 90 min Post: 0, 1 h, 24 h

(*Continued*)

TABLE 1 Continued

Sport	Article	N (male, female)	Age (years)	Level of performance	Study-defined training/competition characteristics	Load parameters	Time point of internal load measurement
(Half-) Marathon	(38)	17 (11,6)	41 ± 6	Recreational runners	Competition was the World Half Marathon Championship in Valencia, Spain	Blood/Plasma creatine kinase and glutamate oxaloacetate transaminase concentration Perception of fatigue and pain were measured using a 150 mm visual analogue scales (VAS)	Pre: 24 h, 48 h Post: 24 h, 48 h
	(39)	16 (9,7)	36 ± 7	Recreational marathon runners	A marathon in a hot environment (thermal stress index = 28.3 ± 3.3°C and humidity −81%)	Blood/Serum creatine kinase, and lactate dehydrogenase concentration	Pre: 45 min Post: 24 h
Other sports	(40)	10 (10,0)	40 ± 6	Recreational triathletes; triathlon experience was 7 ± 3 years	First day: Training cycling: 94 km at an intensity of 70% VO2max including 6k of uphill time trial all-out. 1,800 meters of swimming in the sea at an intensity of 60-70% VO2max. Core training session 45 min) Second day: Training cycling: 156 km + 2,977 elevation meter. 60% of the route at 60%–70% VO2max and 40% of the route at 71%–85% VO2max (uphills). Joint mobility session, no cardiovascular and strength effort (45 min)	Perception of fatigue and pain were measured using a 150-mm visual analogue scale (VAS)	2 days: Pre: 1.25 h and third day in the morning
	(35)	22 (22,0)	Endurance athletes (triathletes and long-distance runners): 24.5 ± 5.4 Sprint athletes: 25.0 ± 3.4	Polish national teams	Treadmill - 3 min of stand followed by - walking for the first 3 min - a speed of 4 km/h, then increased to 8 km/h. Then, the treadmill speed increased by 2 km/h every 3 min until volitional exhaustion of the subject	Blood lactate, ammonia concentration	Pre: Rest Post: 0, 5, 10, 15, 20, and 30 min

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TABLE 2 Characterization of infrared thermography assessment.

Sport	Article	Thermographic parameters	Body region of thermographic assessment	Time point of thermographic assessment	Camera	Analysis Method of thermographic parameters	Statistical method
Studies investigating response to a (partial) season; Soccer	(9)	Mean skin temperature	14 anterior ROIs and 14 posterior ROIs of the leg	Post: 48 h	T450 model thermal camera (FLIR1 Systems, Danderyd, Sweden) was used, with a precision of up to 0.05°C and emissivity of 0.98	Temperature asymmetries were considered when the athlete presented a difference of 1°C between the limbs and reported pain in one body region mean skin temperature asymmetries between corresponding ROIs in the contralateral limbs	Pearson correlation
	(36)	Skin Temperature	Anterior and posterior regions of the lower limbs	Pre: Season Post: Season after an interval of 72 h of inactivity (no training)	T420, FLIR Systems (Stockholm) with measuring range from −20 to +120°C, precision of 1%, sensitivity ≤0.05°C, an infrared spectral band of 7.5 to 13 µm, refresh rate of 60 Hz, autofocus, and resolution of 320 × 240 pixels	Hot zone Tsk percentage (≥33°C) symmetry angle equation were used to identify Tsk asymmetry	Spearman correlation and regression (no details reported)
	(12)	Average, minimum and maximal skin temperature	Anterior and posterior regions of the lower limbs (44 ROIs)	Post: 72 h	FLIR T435bx (FLIR Systems, Sweden) with a resolution of 320 × 240 pixels and thermal sensitivity ≤0.04°C/ <40 mK, was placed 3 m away from the participants and at a perpendicular angle to them, around 60 cm height	Mean Tsk and mean Tsk asymmetries between corresponding ROIs in the contralateral limbs. For asymmetries, every bilateral ROI of the players were classified in a subgroup: low (<0.3°C) or high thermal asymmetry (≥0.3°C). Further calculation based on this subgroups	Product–moment correlations (Pearson *r*)
Studies investigating response to a (partial) season; Other sports, Sprinting, Taper period	(34)	Mean and standard deviation of skin temperature	Anterior and posterior regions of the lower limbs	08:00 and 09:00 and between 20:00 and 21:00 local time; approximately Pre: 1 h, Post: not derivable	FLIR SC640 IR camera (FLIR Systems Inc., model SC640, Sweden)with noise-equivalent temperature difference	Daily skin temperature changes	Spearman correlation
Soccer; Studies investigating response to ≤3 soccer games	(3)	Mean skin temperature	Anterior and posterior regions of the legs	Pre: 24 h Post: 24 h, 48 h	FLIR T420, FLIR Systems Inc., Wilsonville, OR, USA with a measurement range from −20°C to + 120°C, 2% accuracy, sensitivity ≤0.05°C, IR spectral band of 7.5 to 13 µ, refresh rate of 60 Hz, auto-focus and a resolution of 320 × 240 pixels	No further analysis	No further analysis
	(4)	Mean skin temperature	Anterior and posterior side of: right thigh, left thigh, right leg, left leg	Pre: 24 h Post 1st match: 24 h, 48 h Post 2nd match: 24 h, 48 h	FLIR, T420, Flir Systems Inc., Wilsonville, Oregon, USA), with a measurement range from −20 to 120°C, 2% accuracy, sensitivity <0.05°C, IR spectral band of 7.5–13 lm, refresh rate of 60 Hz, auto-focus and a resolution of 320 × 240 pixels	Delta Pre-Post of mean skin temperature	Spearman correlation
	(33)	Skin temperature	Lower limbs (detailed areas n.r.)	Post: 24 h, 48 h, 72 h	T1020, FLIR, Stockholm, with measuring range from − 20 to +120°C, sensitivity ≤0.02°C, refresh rate of 60 Hz, autofocus and FULL HD resolution, 1.5 m distance	Absolute and relative delta in temperature from Pre - Post using the thermal pixelgraphy method, considering pixels compatible with temperatures ≥33°C	Spearman correlation

(*Continued*)

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TABLE 2 Continued

Sport	Article	Thermographic parameters	Body region of thermographic assessment	Time point of thermographic assessment	Camera	Analysis Method of thermographic parameters	Statistical method
Combat/Judo	(7)	Body skin temperature	Body skin temperature were calculated using the equation by Ramanathan: BST = 0.3 × [chest] + 0.3 × [upper arm] + 0.2 × [thigh] + 0.2 × [calf] 4 regions of interest (ROIs) (chest, posterior upper arm, anterior thigh, and anterior calf) on the right side of the body	Pre: 0 min, Post: 0 min, 90 min, 24 h	FLIR T335 thermal camera (FLIR Systems, Danderyd, Sweden) was used with a measurement range from 220 to +1208°C, 2% accuracy, sensitivity # 0.058°C, IR spectral band of 7.5–13 mm, refresh rate of 60 Hz, autofocus, and a resolution of 320 × 240 pixels	Delta Pre-Post of skin temperature	Logistic regression analysis and Pearson correlation
	(37)	Mean skin temperature	Mean skin temperature of the entire body was calculated using the 10 sites, according to the equation of Houdas and Ring (0.06 × forehead) + (0.12 × check) + (0.12 × abdomen) + (0.12 × subscapular) + (0.08 × posterior upper arm) + (0.06 × posterior forearm) + (0.125 × anterior-medial-thigh) + (0.075 × anterior calf) +(0.075 × posterior calf)	Pre: 0 min Post: 5 min, 10 min, 15 min	FLIR T440 (Flir Systems, Inc., Wilsonville, OR, USA) 320 × 240 pixels, thermal sensitivity, 50 mK, and accuracy of 62°C Low-intensity: 40 min at 65% HR_{max}	Delta Pre-Post of mean skin temperature	Linear regression
(Half-)Marathon	(38)	Average temperature, the maximum temperature and the standard deviation	10 ROIs of the full body: (1) anterior upper limbs, (2) posterior upper limbs, (3) abdominal, (4) lumbar back, (5) anterior thigh, (6) posterior thigh, (7) knee, (8) popliteus, (9) anterior leg, and (10) posterior leg mean skin temperature was calculated using the modified equation of Newburg–Spealman (mean = 0.34 * abdomen + 0.15 * posterior forearm + 0.33*posterior thigh + 0.18*posterior leg)	Pre: 24 h, 48 h Post: 24 h, 48 h	E-60, 320 × 240 pixels, Flir Systems Inc. (Wilsonville, OR, USA) with noise-equivalent temperature difference (NETD)	Delta Pre-Post of mean skin temperature and average skin temperature of ROIs	Elastic-net penalized logistic regression model
	(39)	Mean skin temperature	13 ROIs of anterior and posterior limbs	Pre: 15 days, 45 min Post: 24 h and 6 days	T440, FLIR Systems, Wilsonville, OR, USA). The camera had a focal plane size of 320 × 240 pixels with a measurement uncertainty of ±2% and a thermal sensitivity of 0.04°C	Delta Pre (15 days) – Post (24 h) mean skin temperature	Multiple linear regression

(*Continued*)

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TABLE 2 Continued

Sport	Article	Thermographic parameters	Body region of thermographic assessment	Time point of thermographic assessment	Camera	Analysis Method of thermographic parameters	Statistical method
Other sports	(40)	Mean temperature, maximum temperature and the standard deviation	8 ROIs from the upper and lower limbs	2 days: Pre: 1.,25 h and third day in the morning	E60, Flir Systems Inc. (Wilsonville, OR, USA) with noise-equivalent temperature difference (NETD) <0.05° C, focal plane sensor array size of 320 × 240, and measurement uncertainty of ± 2% of the overall operational temperature range	Delta Pre-Post of mean skin temperature and average skin temperature of ROIs	Multiple linear regression
	(35)	Mean skin temperature and standard deviation	Anterior and posterior lower limbs	Pre: Rest Post: 0, 5, 10, 15, 20, and 30 min	FLIR SC640 IR camera (FLIR Systems Inc., SC640 model, Sweden) 640 × 480 pixels, noise-equivalent temperature difference (NETD) <30 mK, temperature accuracy of ±2%	No further analysis	Pearson correlation

n.r., not reported; ROI, region of interest; Tsk, skin temperature.

3.3 Response of IRT to (non-)sport specific exercise and relationship with internal load

Figures 2 and 3 summarize the response of IRT-related parameters to (non-)sport specific exercise.

Tables 3–5 represent the response of IRT related parameters following (non-)sport specific exercise and the relationship with internal load parameters.

3.4 Risk of bias

Table 6 summarizes the risk of bias according to QUADAS-2.

The first domain pertaining patient or participant selection indicates one study (3) with a high risk. De Andrade Fernandes (3) conducted a single-case study. Two studies were classified as unclear risk: Brito et al. (7) did not provide information of medical history, which could have been a part of the applied TISEM Checklist. Rodrigues Júnior (36) et al. utilized inclusion and exclusion criteria, but omitted information about application factors such as ointments or therapies. Applicability concerns regarding patient selection were categorized as unclear risk in studies by Brito et al. (7) and Gomes Moreira et al. (37), due to the potential inclusion of athletes under the age of 18, as indicated by the reported standard deviation of participants' ages. The remaining 11 studies (3, 4, 7, 9, 12, 33–40) incorporate athletes who were suitable for the research question. In the second domain referring to the index test, all 13 studies (3, 4, 7, 9, 12, 33–40) showed a low risk of bias, while there are two studies with unknown risk of applicability concerns. The study of Rojas-Valverde (39) was classified as unclear for applicability, as they reported a cleaning and drying process before IRT assessment but did not provide information about the drying method. Majano et al. (12) classified body areas of every athlete depending on asymmetries on training days. Therefore, a one body part could be classified in low asymmetry group and another part could be classified in high asymmetry group. As there is no additional evidence supporting this methodological approach, it was classified as unclear.

Regarding the reference standard, all 13 studies (3, 4, 7, 9, 12, 33–40) applied parameters, which encompasses defined load states of the athletes and therefore showed no risk of bias. The investigation of Priego-Quesada (40) was classified as unclear risk of concerns in terms of applicability, as they analyzed reported volumes of running and cycling load without providing information how these volumes were recorded.

The fourth domain "Flow and Timing" reflected no risk of bias of any study, since there was no delay or follow-up periods between the index and reference tests.

4 Discussion

The aim of this article was to systematically review available literature on the response of IRT related parameters to (non-) sport specific exercise and relationship with internal load parameters. The main results are:

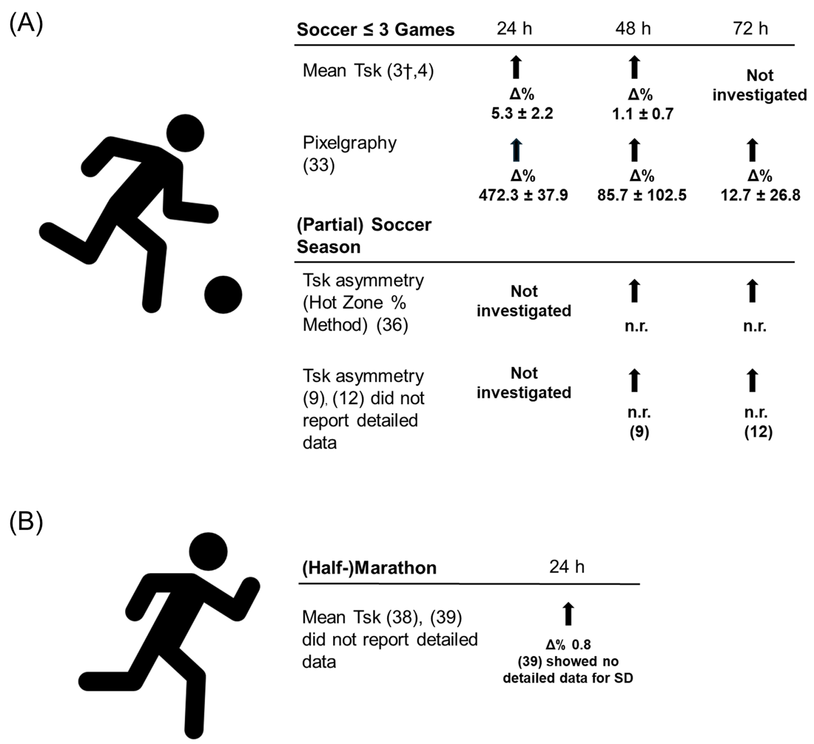

FIGURE 2
Changes in skin temperature in soccer and (half-)marathon. **(A)** Soccer ≤3 games and (partial) soccer season. **(B)** (Half-)Marathon. *Δ%* percentage changes based on mean values prior and after training or competition (self-calculated). †Single case study. Abbreviations: n.r., not reported in the study; Tsk, Skin temperature.

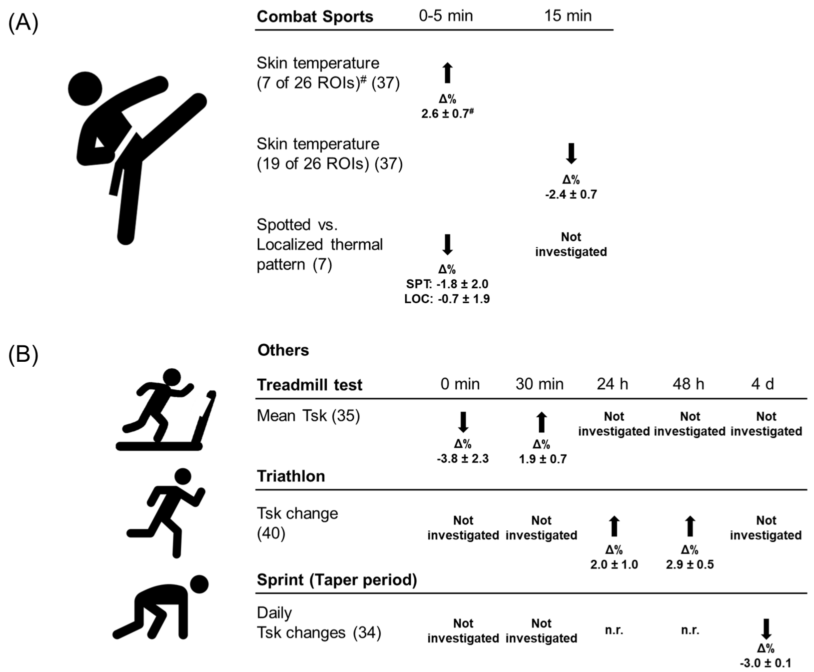

FIGURE 3
Changes in skin temperature in combat sports and other sports. **(A)** Combat sport. **(B)** Other sports (treadmill test, triathlon, sprint). *Δ%* percentage changes based on mean values prior and after training or competition (self-calculated). #calculation based on 6 ROIs, as dataset only includes 6 ROIs with a Tsk increase. Abbreviations: n.r., not reported in the study; Tsk, Skin temperature.

TABLE 3 Infrared related parameter response and relationship with load parameter of studies in soccer investigating response to ≤3 soccer games and combat sport.

Sport	Article	Load				IRT related parameter				Relationship	
		Pre	Post	Δ% (self-calculated)	Sig.	Pre (in °C)	Post (in °C)	Δ% (self-calculated)	Sig.	Relationship	Sig.
Soccer	(3)	CK:	CK:		Single case: n.a.		24 h:		Single case: n.a.	Single case: n.a.	Single case: n.a.
		193 U/L	24 h: 1083 U/L	461.1		Thighs anterior: 31.5	Thighs anterior: 33.8	7.3			
			48 h: 414 U/L	114.5		Legs anterior: 31.2	Legs anterior: 33.3	6.7			
						Thighs posterior: 32.1	Thighs posterior: 34.6	7.8			
						Legs posterior: 31.0	Legs posterior: 33.2	7.1			
							48 h:				
							Thighs anterior: 31.8	1.0			
							Legs anterior: 31.5	1.0			
							Thighs posterior: 32.5	1.2			
							Legs posterior: 31.7	2.3			
	(4)	CK:	First match, 24 h:		All time points to pre: $P = 0.000$	Mean values	First match, 24 h, mean values (self-calculated):		Increase from Pre to Post match 1, 24 h all ROIs: $p < 0.05$ Increase from Pre to Post match 2, 24 h all ROIs: $p < 0.05$ Increase from Pre to Post match 2, 48 h anterior right and left thigh, anterior left leg: $p < 0.05$	CK:	
		221.8 ± 107.6 U/L	763.8 ± 294.5 U/L	244.4		(self-calculated):				Anterior:	Anterior:
			Second match, 24 h:			Anterior: 32.38 ± 3.50 Posterior: 32.50 ± 3.75	Anterior: 33.30 ± 0.38	2.86		Right thigh: $r = 0.345$	$p < 0.01$
			784.1 ± 298.8 U/L	253.5			Posterior: 33.33 ± 0.38	2.54		Right leg: $r = 0.425$	$p < 0.01$
										Left thigh: $r = 0.353$	$p < 0.01$
			First match, 48 h:				Second match, 24 h, mean values (self-calculated):			Left leg: $r = 0.428$	$p < 0.01$
			526.4 ± 289.7 U/L	137.3							
			Second match, 48 h:				Anterior: 33.80 ± 0.30	4.40		Posterior:	
			672.2 ± 285.0 U/L	203.1			Posterior: 33.70 ± 0.30	3.69		Right thigh: $r = 0.276$	$p < 0.05$
										Right leg: $r = 0.289$	$p < 0.05$
							First match, 48 h, mean values (self-calculated):			Left thigh: $r = 0.299$	$p < 0.05$
										Left leg: $r = 0.257$	$p < 0.05$
							Anterior: 32.43 ± 0.45	0.15			
							Posterior: 32.63 ± 0.475	0.38			
							Second match, 48 h, mean values (self-calculated):				
							Anterior: 33.03 ± 0.35	2.01			
							Posterior: 32.78 ± 0.40	0.85			

(*Continued*)

TABLE 3 Continued

Sport	Article	Load				IRT related parameter				Relationship	
		Pre	Post	Δ% (self-calculated)	Sig.	Pre (in °C)	Post (in °C)	Δ% (self-calculated)	Sig.	Relationship	Sig.
	(33)	CRP (mg/L):	CRP (mg/L):			In pixels:	All in pixels:			CRP:	
			Game 1:				Game 1:			Game 1:	
		0.55 ± 0.17	24 h: 2.60 ± 0.86	372.73	$p < 0.001$	9.91 ± 1.36	24 h: 54.99 ± 8.55	454.89	$p < 0.001$	Post (24 h): $r = 0.60$	$p \leq 0.05$
			48 h: 1.65 ± 0.51	200.00	$p < 0.001$		48 h: 10.84 ± 1.73	9.38	$p < 0.04$	Post (48 h): $r = 0.69$	$p \leq 0.05$
			72 h: 0.56 ± 0.18	1.81	n.s. $p > 0.10$		72 h: 14.09 ± 2.11	42.18	$p < 0.001$	Post (72 h): $r = 0.72$	$p \leq 0.05$
			Game 2:				Game 2:			Game 2:	
			24 h: 3.14 ± 0.51	470.90	$p < 0.001$		24 h: 61.02 ± 5.30	515.74	$p < 0.001$	Post (24 h): $r = 0.43$	n.s.
			48 h: 0.73 ± 0.22	32.73	$p < 0.001$		48 h: 14.41 ± 2.52	45.41	$p < 0.04$	Post (48 h): $r = 0.29$	n.s.
			72 h: 0.59 ± 0.22	7.27	n.s. $p > 0.10$		72 h: 10.51 ± 1.50	6.05	n.s. $p > 0.07$	Post (72 h): $r = 0.66$	$p \leq 0.05$
			Game 3:				Game 3:			Game 3:	
			24 h: 3.02 ± 0.63	449.09	$p < 0.001$		24 h: 54.13 ± 9.79	446.22	$p < 0.001$	Post (24 h): $r = 0.21$	n.s.
			48 h: 1.96 ± 0.41	256.36	$p < 0.001$		48 h: 29.95 ± 4.87	202.22	$p < 0.04$	Post (48 h): $r = 0.21$	n.s.
			72 h: 0.71 ± 0.12	29.09	n.s. $p > 0.10$		72 h: 8.91 ± 2.04	−10.09	n.s. $p > 0.07$	Post (72 h): $r = 0.18$	n.s.
	Sum	CK: 2	2 out of 2: Increase (Single case) and significant increase (Both 24, 48 h)			3 out of 3 increases (2 sig., 1 single case) (24, 48, 72 h)					1 out of 1: Relationship with CK, CRP
		CRP: 1	1 out of 1 (24, 48 h)								
Combat	(7)	Leukocytes:	Leukocytes:			Spots Group:			Pre to Post 0 h:	Variation of	$p = 0.34$,
		6.3 ± 1.3	0 h: 8.5 ± 2.0	34.9	$p \leq 0.001$	33.85 ± 0.56	0 h: Spots: 33.22 ± 0.52 Localized: 33.80 ± 0.86	0 h: Spots: −1.86 Localized: −0.69	Spots: $p \leq 0.001$	leukocytes including	n.s.
			1 h: 10.2 ± 3.3	61.9	$p \leq 0.001$	Localized Group:	1 h: Spots: 34.10 ± 0.56 Localized: 34.22 ± 0.74	1 h: Spots: 0.74 Localized: 0.55	Localized:	all data:	
			24 h: 6.5 ± 1.7	3.2	$p \leq 0.001$	34.03 ± 0.69	24 h: Spots: 33.61 ± 0.40 Localized: 33.82 ± 0.65	24 h: Spots: −0.71 Localized: −0.62	$p = 0.043$	$R = 0.16$	
									Post 0 h: Spots lower body skin temperature than Localized: $p = 0.016$	Group results: Spots lower leukocytes and neutrophils than localized	$p \leq 0.001$

(*Continued*)

TABLE 3 Continued

Sport	Article	Load: Pre	Load: Post	Load: Δ% (self-calculated)	Load: Sig.	IRT related parameter: Pre (in °C)	IRT related parameter: Post (in °C)	IRT related parameter: Δ% (self-calculated)	IRT related parameter: Sig.	Relationship: Relationship	Relationship: Sig.
	(37)	Lactate:	Lactate:			34.2 ± 0.5	5 min: 34.3 ± 0.6	0.29	Pre to 15 min:	Difference Tsk 5 min	$p = 0.001$
		1.1 ± 0.3 mmol/L	0 min: 6.4 ± 2.7	481.8	$p \leq 0.001$		10 min: 33.8 ± 0.6	−1.17	$p = 0.002$, 5 min to 10 and 15 min: $p < 0.001$, $p < 0.001$	and Tsk baseline to lactate 0 min post: $r = 0.66$	
			5 min: 5.9 ± 2.4	436.4	$p \leq 0.001$		15 min: 33.5 ± 0.6	−2.05			
			10 min: n.r.	n.r.	n.r.						
			15 min: 4.0 ± 1.9	263.6	$p \leq 0.001$					Difference Tsk 10 min and Tsk baseline to lactate 0 min post: $r = 0.55$	$p = 0.006$
	Sum	Leukocytes: 1	1 out of 1: Significant increase			2 out of 2: Significant decreases (0 h, 15 min Post)				1 out of 1: Relationship with lactate	
		Lactate: 1	1 out of 1: Significant increase (Post 0, 5, 15 min)			1 out of 1: Skin thermal pattern has impact on Tsk (0 h)				0 out of 1: Relationship with leukocyte count 1 out of 1: Skin thermal pattern has impact on leukocytes and neutrophils	

CK, creatine kinase; CRP, C-reactive protein; n.a., not available; n.r., not reported; n.s., not significant; ROI, region of interest; Sig., significance; Tsk, skin temperature. Δ% percentage changes.

1. 11 out of 13 studies were published between 2019 and 2024, indicating rising interest in research around IRT related parameters following (non-)sport specific exercise in athletic populations.
2. Following (non-) sport-specific exercise in athletic populations, the majority of relevant studies showed a decrease in IRT related parameters within 15 min ($n = 3$) (7, 35, 37), while studies showed an increase in IRT related parameters following 30 min ($n = 1$) (35), 24 h ($n = 5$) (3, 4, 38–40), 48 h ($n = 7$) (3, 4, 9, 12, 33, 36, 40), and 72 h ($n = 3$) (9, 12, 33, 36) after exercise cessation.
3. Relationships between alterations in IRT related parameters and other internal load parameters are inconsistent across the literature. Synthetization of literature is impaired due to variety in used methodological approaches (e.g., calculated IRT related parameters, time points of measurement, assessed internal load parameters).

4.1 Soccer

4.1.1 Studies investigating IRT related parameter response to ≤ 3 soccer games and relationship with other internal load parameters

Studies show a response in investigated IRT related parameters (i.e., change in mean Tsk; mean change after 24 h: 5.3%, after 48 h: 1.1%) (3, 4) and change in Tsk using thermal pixelgraphy method (mean change 24 h: 472.3%, after 48 h: 85.7%, after 72 h: 12.7%) (33) 24 h, 48 h and 72 h following a soccer match.

Studies investigating a relationship between mean Tsk and CK (24 and 48 h: anterior leg; mean $r = 0.388$, $p \leq 0.01$; posterior leg; mean $r = 0.280$, $p \leq 0.05$) (4) as well as Tsk evaluated through the thermal pixelgraphy method and CRP after one game (24 h post: $r = 0.60$, $p \leq 0.05$; 48 h post: $r = 0.69$, $p \leq 0.05$; 72 h post: $r = 0.72$, $p \leq 0.05$) and after 2 consecutive games (72 h post: $r = 0.66$, $p \leq 0.05$) (33).

Studies examined a relationship between mean Tsk and CK at a specific time point (24 and 48 h: anterior leg; mean $r = 0.388$, $p \leq 0.01$; posterior leg; mean $r = 0.280$, $p \leq 0.05$) (4) as well as Tsk evaluated through the thermal pixelgraphy method and CRP after one game (24 h post: $r = 0.60$, $p \leq 0.05$; 48 h post: $r = 0.69$, $p \leq 0.05$; 72 h post: $r = 0.72$, $p \leq 0.05$) and with CRP after 2 consecutive games (72 h post: $r = 0.66$, $p \leq 0.05$) (25).

While these studies show that soccer games evoke alterations in IRT related parameters (with 24 h post showing the highest alteration) which seem to have a relationship with CK and CRP, literature is still scarce and further research on response of IRT related parameters and relationship with internal load parameters is needed.

4.1.2 Studies investigating infrared thermography related parameters response to a (partial) season and relationship with other internal load parameters

Three studies investigated IRT related parameters (9, 12, 36) and showed that Tsk asymmetries using the "hot zone percentage method" (72 h post season: $p = 0.0001$) (36) and mean Tsk

TABLE 4 Infrared related parameter response and relationship with load parameter for studies in (half-) marathon, triathlon and treadmill test.

Sport	Article	Load						IRT related parameter						Relationship	
		Pre		Post		Δ% (self-calculated)	Sig.	Pre (in °C)		Post (in °C)		Δ% (self-calculated)	Sig.	Relationship	Sig.
(Half-) Marathon	(38)[a]	48 h: CK: 137.71 (U/L) ± 148.48	24 h: CK: 145.03 (U/L) ± 118.25	24 h: CK: 752.25 (U/L) ± 448.19	48 h: CK: 450.32 (U/L) ± 403.33	24 h Pre to 24 h Post: 418.69	Pre 24 h to Post 24 h: $p < 0.001$	48 h: Mean skin temperature (Newburg-Spielman): 32.26 ± 0.80 Posterior upper limb: 31.11 ± 0.81 Knee: 29.97 ± 1.29	24 h: Mean skin temperature (Newburg-Spielman): 32.73 ± 0.76 Posterior upper limb: 31.94 ± 0.96 Knee: 30.97 ± 1.08	24 h: Mean skin temperature (Newburg-Spielman): 32.51 ± 0.62 Posterior upper limb: 31.89 ± 0.94 Knee: 30.44 ± 0.97	48 h: Mean skin temperature (Newburg-Spielman): 32.69 ± 0.68 Posterior upper limb: 32.39 ± 0.81 Knee: 30.74 ± 1.21	48 h Pre to 24 h Post: Mean skin temperature: 0.77 Posterior upper limb: 2.51 Knee: 1.57	Skin temperature Pre 48 h to Post 24 h: Increase in posterior upper limb: $p < 0.001$	Differences between measurement 24 h post half marathon and average of the measurements 24 h and 48 h before half marathon: posterior upper limb: ΔCK24 - ΔT24: $r = 0.5$	$p = 0.04$
		48 h: GOT (U/L): 33.67 ± 11.53	24 h: GOT (U/L): 34.52 ± 10.17	24 h: GOT (U/L): 74.56 ± 52.00	48 h: GOT (U/L): 64.3 ± 45.40	24 h Pre to 24 h Post: 115.99	24 h Pre to 24 h Post: $p < 0.04$							GOT: n.s.	
		48 h: Pain: 1.05 ± 1.26	24 h: Pain: 1.14 ± 0.93	24 h: Pain: 4.71 ± 3.18	48 h: Pain: 4.36 ± 3.01	24 h Pre to 24 h Post: 313.16	24 h Pre to 24 h Post: $p < 0.001$							knee: Δoverallpain 48 - ΔT48: $r = 0.6$	$p < 0.01$
		48 h: Fatigue: 1.51 ± 1.43	24 h: Fatigue: 1.89 ± 1.57	24 h: Fatigue: 6.54 ± 3.03	48 h: Fatigue: 5.46 ± 2.80	24 h Pre to 24 h Post: 246.03	24 h Pre to 24 h Post: $p < 0.001$							Fatigue: n.s.	
		48 h: CMJ height: 24.4 cm ± 4.1	24 h: CMJ height: 25.0 cm ± 4.9	24 h: CMJ height: 23.4 cm ± 4.0	48 h: CMJ height: 24.6 cm ± 4.5	24 h Pre to 24 h Post: −6.40	24 h Pre to 24 h Post: $p < 0.01$							CMJ: n.s.	
	(39)	CK: 174.3 UI/L ± 136.4		CK: 1159.7 UI/L ± 699.7		565.35	$p < 0.01$	n.r.		n.r.		n.a.	Significant increases from Pre 15 days to Post 24 h: All ROIs (except Semi-tendinous $p < 0.01$): $p < 0.001$		n.s. $p > 0.21$
		LDH: 362.6 UI/L ± 99.9		LDH: 438.0 UI/L ± 115.5		20.79	$p = 0.02$								
	Sum	CK: 2				2 out of 2: Significant increase (Post 24 h)		2 out of 2: Significant increase (Both post 24 h)						1 out of 1: Relationship with pain 1 out of 2: Relationship with CK 0 out of 1: Relationship with GOT, LDH, fatigue, CMJ height	
		GOT: 1				1 out of 1: Significant increase (Post 24 h)									
		LDH: 1				1 out of 1: Significant increase (Post 24 h)									
		Perception of pain: 1				1 out of 1: Significant increase (Post 24 h)									
		Perception of fatigue: 1				1 out of 1: Significant increase (Post 24 h)									
		CMJ height: 1				1 out of 1: Significant decrease (Post 24 h)									

(*Continued*)

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TABLE 4 Continued

Sport	Article	Load				IRT related parameter				Relationship	
		Pre	Post	Δ% (self-calculated)	Sig.	Pre (in °C)	Post (in °C)	Δ% (self-calculated)	Sig.	Relationship	Sig.
Triathlon	(40)[a]		24 h: / 48 h:	24 h Post:		Knee: 28.4 ± 1.1 Posterior leg: 29.2 ± 0.8	24 h: Knee: 29.3 ± 0.5	3.17	$p < 0.01$	Δ48 h knee fatigue and Δ48 h anterior knee Tsk: $R^2 = 0.5$ (inverse) No relationship with pain and overall fatigue	$p = 0.03$
		Fatigue; Overall: 2.2 ± 2.2	24 h: Fatigue; Overall: 4.5 ± 3.1 48 h: Fatigue; Overall: 5.7 ± 3.2	Fatigue; Overall: 104.55	Overall: 24 h: $p <$ 0.05, 48 h: $p < 0.01$		Posterior leg: 29.4 ± 0.8	0.68	n.s.		
							48 h: Knee: 29.4 ± 1.0	3.52	$p < 0.01$		
		Knee: 0.3 ± 0.5	24 h: Knee: 1.8 ± 2 48 h: Knee: 2.2 ± 2.4	Knee: 500.00	Knee: 24 h, 48 h: n.s.		Posterior leg: 29.8 ± 0.8	2.05	$p < 0.05$		
				48 h Post: Fatigue; Overall: 159.09 Knee: 633.33						Δ24 h posterior knee Tsk and reported cycling and running volume: R2 = 0.7	$p < 0.01$
		Pain: Overall: 2.2 ± 2.6	24 h: Pain; Overall: 3.5 ± 2.7 48 h: Pain; Overall: 3.9 ± 2.6	24 h Post: 59.09 48 h Post: 77.27	Pain; Overall: 24, 48 h: n.s.					Δ24 h posterior leg Tsk and reported cycling volume: $R^2 = 0.44$	$p < 0.04$
		Reported running, cycling and swimming volume: 28 ± 12 km, 159 ± 61 km and 5 ± 2 km			n.r.						
Treadmill Test	(35)	Lactate (mmol/L):	Lactate (mmol/L):		Pre to Post: n.r.	Endurance group:	Endurance group:		Pre to Post comparison n.r.	Skin temperature - Lactate correlations: Between the 10th and 30th minute of recovery; r ranging from −0.54 to −0.45	$p < 0.05$
		Endurance group:	Endurance group:			31.74 ± 0.73	0 min: 30.02 ± 1.07	−5.42			
		1.05 ± 0.35	0 min: 10.17 ± 1.49	868.57			5 min: 31.64 ± 1.08	−0.32			
			5 min: 8.96 ± 1.80	753.33			10 min: 31.78 ± 1.17	0.13			
			10 min: 7.43 ± 1.91	607.62			15 min: 31.93 ± 1.12	0.60			
			15 min: 6.15 ± 1.73	485.71			20 min: 32.12 ± 1.06	1.20			
			20 min: 5.04 ± 1.67	380.00			30 min: 32.49 ± 0.81	2.36			
			30 min: 3.58 ± 1.24	240.95							
		Ammonia (mmol/L):	Ammonia (mmol/L):		Pre to Post: n.r.	Sprint group: 32.26 ± 0.58	Sprint group:		Pre to Post comparison n.r.	Skin temperature - Lactate correlations: Between the 10th and 30th minute of recovery; r ranging from −0.54 to −0.45	$p < 0.05$
		Endurance group:	Endurance group:				0 min: 31.55 ± 0.75	−2.20			
		21.18 ± 6.29	0 min: 75.64 ± 11.51	257.13			5 min: 32.39 ± 0.61	0.40			
			5 min: 65.55 ± 10.30	209.49			10 min: 32.32 ± 0.58	0.19			
			10 min: 52.55 ± 8.72	148.11			15 min: 32.26 ± 0.66	0.00			
			15 min: 43.36 ± 7.68	104.72			20 min: 32.38 ± 0.58	0.37			
			20 min: 34.27 ± 6.50	61.80			30 min: 32.70 ± 0.53	1.36			
			30 min: 27.55 ± 7.43	30.08							
		Lactate (mmol/L):	Lactate (mmol/L):							n.s. correlations between Tsk and ammonia	n.s.
		Sprint group:	Sprint group:								
		1.18 ± 0.30	0 min: 10.14 ± 1.40	759.32							
			5 min: 9.03 ± 1.60	665.25							
			10 min: 7.55 ± 1.44	539.83							
			15 min: 6.10 ± 1.48	416.95							
			20 min: 4.95 ± 1.24	319.49							
			30 min: 3.50 ± 1.03	196.61							
		Ammonia (mmol/L):	Ammonia (mmol/L):								
		Sprint group:	Sprint group:								

(*Continued*)

TABLE 4 Continued

Sport	Article	Load				IRT related parameter				Relationship	
		Pre	Post	Δ% (self-calculated)	Sig.	Pre (in °C)	Post (in °C)	Δ% (self-calculated)	Sig.	Relationship	Sig.
		18.91 ± 3.48	0 min: 76.73 ± 9.03	305.76							
			5 min: 68.45 ± 10.64	261.98							
			10 min: 57.36 ± 9.73	203.33							
			15 min: 48.55 ± 8.64	156.74							
			20 min: 40.09 ± 6.67	112.00							
			30 min: 29.82 ± 5.31	57.69							
	Sum	Ammonia: 1	n.r.			1 out of 2: Significant increase (Post 24 h and Post 48 h) 1 out of 2: Increase				1 out of 1: Relationship with fatigue (knee), lactate, reported training volume 0 out of 1: Relationship with ammonia, pain, overall fatigue	
		Lactate: 1	n.r.								
		Perception of pain: 1	0 out of 1: Significant (Post 24, 48 h)								
		Perception of fatigue: 1	1 out of 1: Significant increase (Post 24, 48 h; Overall fatigue)								
		Reported training volume: 1	n.r.								

CMJ, countermovement jump; CK, creatine kinase; GOT, glutamate oxaloacetate transaminase; LDH, lactate dehydrogenase; n.a., not available; n.r., not reported; n.s., not significant; ROI, region of interest; Sig., significance; Tsk, skin temperature. Δ% Percentage changes.

[a]Only significant results.

asymmetries (mean Tsk asymmetry over entire season: 1.58 ± 0.84) (9, 12) are altered 72 h after a competitive season (36) and 48 h (9) after soccer matches. Majano et al. (12) (72 h after soccer matches) did not represent altered data for Tsk asymmetries.

While a study investigating ≤ 3 soccer games showed a positive relationship between IRT related parameters and CK (4), a finding which is further supported by a single case study (3), the study of de Carvalho (9) indicated no relationship between CK and IRT related parameter (48 h after soccer matches: mean r = 0.07, no *p*-values available) (9). We can only speculate on the reasons for this difference, but the study of de Carvalho (9) exclusively included thermographic images in the data analysis that exhibited Tsk asymmetries of ≥1.0°C, while e.g., Majano et al. (12) utilized a Tsk of 0.5°C to distinguish between athletes indicating a high or low Tsk response. While it was previously argued to use Tsk asymmetries of ≥1.0°C as abnormal side-to-side difference (5, 25, 41), due to advancements in IRT device accuracy, nowadays a lower temperature difference is often used (25).

Two studies (9, 12) assessed relationship between Tsk related parameters and subjective load parameters such as perception of pain, recovery, stress or rest. One (12) out of two showed a relationship between subjective parameters. Majano et al. (12) reported positive correlations between mean skin temperature and muscle soreness (central upper thigh, outer front thigh: r = 0.230, $p \leq 0.05$, respectively), RPE (knee: r = 0.209, $p \leq 0.05$) and stress (ankle: r = 0.153, $p \leq 0.01$) as well as for thermal asymmetry between bilateral ROIs and muscle soreness (outer front thigh: r = 0.234, $p \leq 0.05$; front adductor: r = 0.174, $p \leq 0.01$) and RPE (knee: r = 0.242, $p \leq 0.05$). They indicated negative correlations between mean skin temperature and rest (inner back leg: r = −0.202, $p \leq 0.05$; knee: r = −0.201, $p \leq 0.05$), as well as between thermal asymmetry in bilateral ROIs and rest quality (outer upper thigh: r = −0.172, $p \leq 0.01$) and RPE (central front thigh: r = −0.181, $p \leq 0.01$) (12). While we can only speculate on the reasons for this difference, Carvalho et al. (9) exclusively included athletes who reported pain scores above a threshold of 4, while the study of Majano did not use a threshold for pain scores (12). The difference in the used thresholds for pain scores in the studies (9, 12) could explain the different results.

A strong correlation between Tsk asymmetries and rate of force development assessed using a countermovement jump (mean r = 0.66, mean $r^2 = 0.44$, mean $p = 0.04$) were examined following a competitive soccer season (36). The same study did not find relationships between the calculated impulse and peak force.

Collectively, but taken into consideration that literature is scarce, studies show that IRT related parameters are altered following a (partial) soccer season, which is in line with literature investigating IRT related parameters response to ≤3 soccer games. IRT related parameters seem to have a relationship with internal load such as subjective parameters and RFD measured by CMJs in studies investigating a (partial) soccer season. Interestingly, relationships between CK and IRT related parameters could not be established in studies investigating a (partial) soccer season, which could be due to different methodological approaches. However, as literature is scarce, more

TABLE 5 Characteristics of (partial) season and relationship with internal load parameter in studies investigating response to a (partial) season.

Sport	Article	Characteristics of (partial) season	Thermographic region	Relationship with internal load			
Soccer	(9)	CK: 805.7 ± 560.5 IU/L, mean time in a match (min): 90.16 ± 10.74, total distance covered (m): 9017.04 ± 1621.48, high-intensity distance (m): 1140.90 ± 494.61, total number of high-intensity acceleration (m): 15.60 ± 7.68 and total number of high-intensity deceleration (m): 22.60 ± 8.97	Lower limb anterior total area	CK: $r = 0.03$	n.s.	Pain:	
						$r = -0.18$	n.s.
						Fatigue:	
						$r = -0.19$	n.s.
						Recovery:	
						$r = 0.13$	n.s.
			Lower limb posterior total area	CK: $r = 0.10$	n.s.	Pain:	
						$r = -0.13$	n.s.
						Fatigue:	
						$r = -0.19$	n.s.
						Recovery:	
						$r = 0.10$	n.s.
	(36)	Tsk: 72 h post season: $p = 0.0001$	Anterior region of lower limbs	Group 1:			
				Symmetry angle of peak force: $r = 0.44$			n.s.
				Symmetry angle of impulse: $r = 0.31$			n.s.
				Symmetry angle of the rate of force development: $r = 0.62$			$p = 0.05$, $r^2 = 0.39$
			Posterior region of lower limbs	Group 1:			
				Symmetry angle of peak force: $r = 0.13$			n.s.
				Symmetry angle of impulse: $r = 0.14$			n.s.
				Symmetry angle of the rate of force development: $r = 0.19$			n.s.
			Anterior region of lower limbs	Group 2:			
				Symmetry angle of peak force: $r = 0.61$			n.s.
				Symmetry angle of impulse: $r = 0.22$			n.s.
				Symmetry angle of the rate of force development: $r = -0.13$			n.s.
			Posterior region of lower limbs	Group 2:			
				Symmetry angle of peak force: $r = 0.22$			n.s.
				Symmetry angle of impulse: $r = 0.15$			n.s.
				Symmetry angle of the rate of force development: $r = 0.70$			$p = 0.03$, $r^2 = 0.48$
	(12)[a]	We refer to the article of Majano et al. (12).	Outer upper thigh	Asymmetry: Rest: $r = -0.172$			$p \leq 0.01$
				Mean skin temperature: Muscle Soreness: $r = -0.230$			$p \leq 0.05$
			Central upper thigh	Mean skin temperature: Muscle Soreness: $r = -0.217$			$p \leq 0.05$
			Outer front thigh	Asymmetry: Muscle soreness: $r = 0.234$			$p \leq 0.05$
			Central front thigh				$p \leq 0.01$

(*Continued*)

TABLE 5 Continued

Sport	Article	Characteristics of (partial) season	Thermographic region	Relationship with internal load	
				Asymmetry: Rating of perceived exertion: $r = -0.181$	
			Front adductor	Asymmetry: Muscle soreness: $r = 0.174$,	$p \leq 0.01$
				Stress: $r = 0.260$	$p \leq 0.05$
				Rest: $r = -0.181$	$p \leq 0.01$
				Mean skin temperature: Stress: $r = -0.161$	$p \leq 0.01$
			Inner front thigh	Mean skin temperature: Stress: $r = -0.186$	$p \leq 0.01$
			Inner back leg	Mean skin temperature: Rest: $r = -0.202$	$p \leq 0.05$
			Knee	Asymmetry: Rating of perceived exertion: $r = 0.242$ Mean skin temperature: Rest: $r = -0.201$, Rating of perceived exertion: $r = 0.209$	$p \leq 0.05$
			Ankle	Mean skin temperature: Stress: $r = 0.153$	$p \leq 0.01$
Sprinting	(34)	The baseline level of CK at the beginning of the camp was 146 ± 62 U/L in the female athletes and 236 ± 121 U/L in the male athletes. In both groups CK levels peaked on the second day ($p < 0.01$, female: $\Delta = 178$, male: $\Delta = 163$). The second increase in CK level in the male group occurred between 8th and 11th day ($p < 0.01$, 8th: $\Delta = 156$, 9th: $\Delta = 209$, 10th: $\Delta = 274$, 11th: $\Delta = 188$) with a peak value on the 10th day (510 ± 121 U/L, $p < 0.01$). In the case of the female group, there was no further increase in CK levels by the end of the camp.		CK: n.r.	n.s.
	Sum	CK: 2 Subjective load: 2 CMJ related parameters (RFD, impulse, peak force): 1		1 out of 2: Relationships (positive and negative) with various subjective load parameters (e.g., fatigue, pain, stress, sleep) 0 out of 2: Relationship with CK 1 out of 1: Relationships with RFD (same study showed no relationship with impulse and peak force)	

CMJ, countermovement jump; CK, creatine kinase; CRP, C-reactive protein; n.r., not reported; n.s., not significant; RFD, rate of force development; Tsk, skin temperature.
[a]Only significant results.

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TABLE 6 Risk of bias assessment.

Study	Risk of bias				Applicability concerns		
	Patient selection	Index test	Reference standard	Flow and timing	Patient selection	Index test	Reference standard
(3)	HR	LR	LR	LR	LR	LR	LR
(4)	LR	LR	LR	LR	LR	LR	LR
(7)	UR	LR	LR	LR	UR	LR	LR
(9)	LR	LR	LR	LR	LR	LR	LR
(12)	LR	LR	LR	LR	LR	UR	LR
(33)	LR	LR	LR	LR	LR	LR	LR
(34)	LR	LR	LR	LR	LR	LR	LR
(35)	LR	LR	LR	LR	LR	LR	LR
(36)	UR	LR	LR	LR	LR	LR	LR
(37)	LR	LR	LR	LR	UR	LR	LR
(38)	LR	LR	LR	LR	LR	LR	LR
(39)	LR	LR	LR	LR	LR	UR	LR
(40)	LR	LR	LR	LR	LR	LR	UR

HR, high risk; LR, low risk; UR, unclear risk.

research is needed on the response of IRT related parameters and their relationship with internal load parameters.

4.2 (Half-)marathon

2 out of 2 studies showed elevations in IRT related parameters [Differences in mean skin temperature and ROIs (38, 39)], 24 h after a (half-)marathon in upper and/or lower leg muscles compared to time points prior to the competition (i.e., 48 h prior or 15 days prior) (38, 39).

Relationships between IRT related parameters and CK are non-conclusive following a (half-)marathon. While one study (38) showed a relationship between mean Tsk and CK (24 h post and average of 24 and 48 h post half-marathon, respectively; posterior upper limb: $r = 0.5$, $p = 0.04$) after a half-marathon, another could not identify a relationship between differences in mean Tsk and CK ($p > 0.21$) 24 h after exercise cessation (39). While we can only hypothesize on the reasons for the absence of a relationship in the study of Rojas-Valverde (39), Pérez-Guarner et al. (38) collected IRT related parameter data 24 and 48 h before a half-marathon, whereas Rojas-Valverde (39) analyzed IRT related parameter data from 15 days prior to a marathon.

Additionally, the hot environment in the study of Rojas-Valverde et al. (39) could confound Tsk results. There is evidence indicating that hot conditions may impair physiological responses (42), suggesting that Tsk could also be affected. Future research is required to understand how environmental conditions could impact Tsk responses.

Mean Tsk indicated a relationship with perception of overall pain (48 h post and average of 24 and 48 h post half-marathon: $r = 0.6$, $p < 0.01$) (38). Other analysis of the herein included articles did not show a relationship of mean Tsk with lactate dehydrogenase (39), glutamate oxaloacetate transaminase, fatigue, and CMJ height (38) following a (half-)marathon.

Collectively, there is evidence that IRT related parameters are altered 24 h after a (half-)marathon, yet synthetization of relationships with other internal load parameters is impaired due to low number of studies with different methodological approaches.

4.3 Combat sports

Two studies (7, 37) investigated IRT related parameters following combat sports and their relationship with other internal load parameters are difficult to summarize as they use different methodological approaches (e.g., measured IRT related parameters, internal load parameters, exercises).

Out of all studies in this review, the study of Brito et al. (7) reported different skin thermal patterns denoted as "spots" (SPT) and "localized" (LOC). The study showed lower temperatures for SPT and LOC immediately post training (7).

The study of Gomes Moreira et al. shows that skin temperature changes differ with respect to the region of interest in the minutes after cessation of exercise (37). While 7 regions of interest show an increase in skin temperature following 5 min of exercise (without an increase of mean skin temperature), 15 min post exercise 19 out of 26 regions of interest show a significant decrease in temperature (37). Gomes Moreira et al. thereby argues that post-training epithelial temperature is sensitive to organic variations and proposes that IRT related parameters can be applied as an indication of the intensity exerted after exertion (37), yet more studies are required to strengthen this assumption.

One of the main results of Brito et al. (7) is that skin thermal pattern, and not body skin temperature, defined by the equation of Ramanathan (43), correlates with internal load parameters. Specifically, Brito et al. (7) showed that a spotted skin pattern has a lower skin temperature ($p = 0.016$), blood leukocytes and neutrophils concentration ($p \leq 0.001$) post-training compared to a localized skin thermal pattern. While skin thermal patterns have been investigated in other studies with athletic populations e.g., during exercise (44, 45), Brito et al. (7) acknowledges that more studies are needed which investigate the relationship between skin thermal pattern and immune response following exercise.

The main result of the study of Gomes Moreira et al. (37) shows that concentration of blood lactate at the end of a judo specific incremental test can be explained by the mean Tsk variation 5 ($r = 0.66$, $p = 0.001$) and 10 min ($r = 0.55$, $p = 0.001$) after the test. While literature is scarce, further investigations in athletic populations are needed, IRT related parameters could be useful to determine lactate post exercise non-invasively.

4.4 Other sports

Following a non-specific treadmill test, sprint and endurance athletes showed lower mean Tsk immediately after, (Tsk change in%; endurance group: −5.42 at 0 min, −0.32 at 5 min; sprinter group: −2.20 at 0 min) and a rise in mean Tsk 30 min post exercise (Tsk change in%; endurance group: 2.36 at 30 min, sprinter group: 1.36 at 30 min) (35). After treadmill testing, IRT related parameters indicated a relationship with lactate between the 10th and 30th minute after the testing (r ranging from −0.54 to −0.45, $p < 0.05$), but no relationship with ammonia (35).

In a training camp, triathletes showed an increase in all ROIs (Tsk change in%, e.g., knee: after 24 h: 3.17, after 48 h: 3.52; posterior leg: after 24 h: 0.68, 48 h: 2.05). IRT related parameters indicated an inverse relationship with the perception of knee fatigue (differences in knee fatigue and anterior knee Tsk: $R2 = 0.5$, $p = 0.03$) after two days of training, while no relationships were indicated with perception of pain and overall fatigue (40).

During a 10 day training camp in sprinters which included not further specified "very high intensity and low volume training", a study noted a significant, continuous decrease in IRT related parameters (skin temperature) measured in the morning and evening for both genders (baseline: males 33.7 ± 0.4°C, females 32.8 ± 0.6°C; day 4: males 32.7 ± 0.3°C, females 31.8 ± 0.6°C, $p < 0.05$) (34). This downward trend persisted in males from day 6 till the end of the study and females from day 8 to the 10th day ($p < 0.01$) (34). While the authors (34) indicated an increase in CK concentration in male and female athletes on day two ($p < 0.01$) and a second CK concentration increase in male athletes between day 8 and 11 ($p < 0.01$), they did not exhibit a correlation between IRT related parameter and CK.

4.5 Limitations

This systematic review highlighted concerns about the lack of well-designed, and appropriately reported research in this field as indicated by our risk of bias assessment, as several studies neglected to provide transparent and complete information on methodological standardization. In accordance with Fernández-Cuevas et al. (25) and Moreira et al. (23), appropriate measurements, adherence to operational standards and consistent reporting are essential to ensure the interpretability of data across studies. As systematic reviews rely on the available research, this inconsistency in reporting represents a notable limitation. An additional limitation is the exclusion of studies involving participants under the age of 18, which may have led to the omission of insightful research. This exclusion criterion was established before the search process due to the potential influence of puberty on skin temperature (26). Accordingly, further research is required to investigate post-exercise skin temperature variations across different age groups, as suggested by Fernández-Cuevas et al. (25). Finally, our results only allow limited conclusions regarding the applicability of IRT to assess internal load in sports practice due to an inconsistency in employed methodological approaches (e.g., in assessed IRT parameters, blood-based parameters) and more research is needed which elucidated physiological mechanisms resulting in an alteration in IRT related parameters.

4.6 Recommendations for future research

The present review reveals that more studies are being performed on the use of IRT to assess internal load in different athletic populations since 2019 and that different IRT related parameters are altered following training and/or competition in athletic populations. Physiological mechanisms explaining IRT alterations in athletic populations following training and/or competition are not fully elucidated and need further investigations. From a physiological perspective, micro-damage to muscle cells leads to the release of damage-associated molecular patterns that stimulates resident cells to produce pro-inflammatory mediators (14). These mediators induce vasodilation and alter vessel permeability, increasing blood flow and promote edema (14). Additionally, stimulated endothelial cells express cell adhesion molecules and produce chemoattractant mediators, leading to the infiltration of leukocytes (14, 17, 46). The accumulation of leukocytes is a significant source of cytokines such as TNF-α, interleukin-1β and interleukin-6 (17). Research suggest that these cytokines exhibit pyrogenic properties (47, 48). In consequence, the primary inflammatory responses stimulate phagocytosis and the activation of the complement system to augment tissue repair (14, 16, 17, 46, 49, 50). These pathways may enhance local metabolic rates, substrate utilization, and energy generation, facilitating heat transfer from deeper tissue layers to the body surface, ultimately raising skin temperature (3, 6, 8, 33). Consequently, especially inflammatory parameters (such as CRP, pentraxin-3, prostaglandins, interleukins, TNF-α) (14–16, 49, 51, 52) need to be assessed in future studies.

As some studies in our review did not describe external load to which athletes were exposed in detail, comparisons between studies are impaired. To better compare future studies, we recommend researchers to report details on performed exercises which (depending on the sport) e.g., can include derivatives of GPS-data such as velocity, or accelerations. Additionally, future studies should control or at least report potential effect of factors known to confound IRT, such as food intake prior to image taking (25, 53), or body mass index (54). Our review reveals that different parameters can be calculated from IRT, including e.g., differences of mean Tsk, Tsk asymmetry, calculations of entire body skin temperature. While it is currently still unclear which IRT related parameters has the best relationships with other internal load parameters, it seems recommendable to assess and report a variety of IRT related parameters. To advance our understanding, we recommend also to report such relationships between IRT related parameters and other internal load variables if the relationship is non-existing.

5 Conclusions

Quantifying internal loads holds a key role to individualize training procedures, yet is often impaired e.g., due to invasiveness of methodological approaches, a limitation which might be overcome by IRT related parameters. Our systematic review reveals that the majority of relevant studies showed a decrease in IRT related parameters within 15 min, while increases in IRT related parameters are reported following 30 min, 24 h, 48 h, and 72 h after exercise cessation. Synthetization of the literature regarding relationship of IRT related parameters with other internal load parameters is impaired due to variety in used methodologies and is thereby non-conclusive across different sports. Future studies should carefully follow established recommendations to standardize IRT analyses and available literature. It seems recommendable to investigate the relationships with parameters known to elicit temperature in more detail. Athletes and coaches might detect changes in IRT related parameters following exercise cessation, but detailed physiological mechanisms leading to such change are currently unclear and it seems recommendable to use IRT parameters in conjunction with other load parameters.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

LM: Data curation, Software, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Investigation. FB: Conceptualization, Resources, Writing – review & editing. PD: Project administration, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2024.1479608/full#supplementary-material

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The relationship and agreement between systemic and local breakpoints in locomotor and non-locomotor muscles during single-leg cycling

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Introduction: There is a well-established relationship between the respiratory compensation point (RCP) and local muscular breakpoints determined from near-infrared spectroscopy (NIRS) and electromyography (EMG). However, these breakpoints have not yet been compared both in locomotor and non-locomotor muscles simultaneously in single-leg cycling exercise. Therefore, the aim of the study was to investigate the relationship and agreement between systemic and local breakpoints in locomotor and non-locomotor muscles.

Method: Data from twelve physically-active participants (25.5 ± 3.9 years, 176.1 ± 11.6 cm, 71.2 ± 9.4 kg, 4 females) who completed a continuous single-leg step incremental cycling test (10 W min^{-1}) with their right leg were included in the analysis. Ventilation and gas exchange were recorded to determine RCP. Surface EMG (sEMG) and NIRS signals were measured from both vasti lateralis muscles and breakpoints were determined from root mean Q square sEMG and deoxygenated hemo- and myoglobin signal m[HHb].

Results: There was no significant difference in the power output at RCP (127.3 ± 21.8 W) and local muscular breakpoints both from the locomotor (m[HHb]: 119.7 ± 23.6 W, sEMG: 126.6 ± 26.0 W) and non-locomotor (m[HHb]: 117.5 ± 17.9 W, sEMG: 126.1 ± 28.4 W) muscles. Breakpoints also showed significant ($p < 0.01$) correlations ($r = 0.67–0.90$, ICC = 0.80–0.94) to each other with weaker correlations in the non-locomotor muscle ($r = 0.66–0.86$, ICC = 0.74–0.90). Despite the strong correlations, high individual variability and weak limits of agreement (up to −32.5–46.5 W) and substantial absolute differences (10.2–16.7 W) were observed which indicates that these breakpoints cannot be used interchangeably.

Discussion: These findings offer further insights into the mechanistic relationship between local and systemic physiological response to exercise with increasing workload. We conclude that, despite strong correlations, local muscular breakpoints do not have to coincide with systemic boundaries of physiological domains.

KEYWORDS
respiratory compensation point, near-infrared spectroscopy, electromyography, threshold, metabolic responses, physiological responses

1 Introduction

The determination of breakpoints (also referred as thresholds or turn points) to demarcate three intensity zones with distinctive metabolic properties (Binder et al., 2008; Hofmann and Tschakert, 2011) is relevant for exercise and sports practice. Several methodological approaches exist to determine these breakpoints. Most of these methods are based on systemic adaptions to increasing exercise intensity, e.g., based on blood lactate concentration, gas exchange variables, or heart rate (Meyer et al., 2005) while others are related to the local adaptions of the muscles. A common systemic breakpoint is the respiratory compensation point (RCP) which demarcates the transition from heavy to severe exercise intensity and is determined by the performance depending changes in the curse of oxygen uptake and carbon dioxide output in relation to ventilation (Beaver et al., 1986). The local breakpoints are based on muscular activity measured by electromyography (EMG) signals (e.g., root mean square EMG) or muscular oxygenation measured by near-infrared spectroscopy (NIRS signals) (Boone et al., 2016b). Typically, root mean square (RMS) values or mean power frequency from EMG (Ertl et al., 2016) and oxygenated (O_2 [HHb]) and deoxygenated (m[HHb]) hemoglobin and myoglobin, total amount of tissue heme (totalHb), and tissue saturation (SmO_2) values from NIRS (Perrey et al., 2024) are used to determine these breakpoints. It has been shown consistently that systemic and local breakpoints are observed at similar intensities during exercise testing. However, there is still an ongoing debate if there is a mechanistic relationship between local and systemic breakpoint concepts (Caen and Boone, 2023; Goulding et al., 2023).

Boone et al. (2016b) provided a theoretical framework that represents the relationship between muscular activity, metabolic processes, ventilation (VE), and (cerebral) blood flow which may explain the possible mechanistic link between different breakpoint concepts. Noticeably, apart from respiratory muscles that increase in activation due to the need for increased respiration (Contreras-Briceño et al., 2022), non-locomotor muscles are not included in this framework. However, several studies already investigated the behavior of non-locomotor muscles of the arm during lower limb exercises and reported increased blood flow (Tanaka et al., 2006) and decreased oxygenation in the inactive limb (Shiroishi et al., 2010; Özyener et al., 2012; Yogev et al., 2022; Sendra-Pérez et al., 2024a). This indicates that non-locomotor muscles are related to locomotor muscles through the systemic blood flow. Hence, local breakpoints in variables based on blood flow, e.g., based on NIRS signals should be observable in non-locomotor muscles. As a consequence, the framework between systemic and local breakpoints by Boone et al. (2016b) could be augmented by non-locomotor muscles. Indeed, Ogata et al. (2004), Yogev et al. (2022), and Sendra-Pérez et al. (2023) reported that breakpoints in NIRS signals of non-locomotor upper limb muscles during ramp leg exercises coincide with the respiratory compensation point (RCP) which is determined from systemic spirometry variables and demarcates the intensity for the transition from steady state to non-steady state exercise conditions. However, in contrast to breakpoints from NIRS signals, local breakpoints based on muscular activity (EMG) should not be observable in non-locomotor muscles as they are assumed to not increase activation during the increase of exercise intensity. Although such an observation would strengthen the framework by Boone et al. (2016b), this has not been tested yet.

Therefore, the aim of the study was to investigate the relationships and agreement between systemic and local breakpoints in locomotor and non-locomotor muscles. Our hypotheses were twofold: First, in the locomotor muscles we hypothesized a relationship and agreement between RCP determined from systemic variables and local muscle breakpoints based on muscular activity (sEMG, RMS) and oxygenation (NIRS, m[HHb]). Second, in non-locomotor muscles we hypothesized a relationship and agreement between RCP and the local breakpoint based on oxygenation (NIRS, m[HHb]) but not based on muscular activity (sEMG, RMS).

2 Methods

2.1 Participants

Boone et al. (2016a) reported a significant relationship ($r = 0.91$, $p < 0.01$) between the breakpoints of deoxygenated hemo- and myoglobin ($m[HHb]_{BP}$) and integrated sEMG (EMG_{BP}) signals. Based on these results, a minimum of eight participants was calculated (using G*Power software, Faul et al., 2007) to achieve a significant relationship between the breakpoints in our study. To account for technical problems and possible non-responders, 13 participants (4 females) were included in the study. Data from one participant had to be discarded due to a tattoo on the thigh, which affected the NIRS data. Therefore, 12 participants (4 females, 25.5 ± 3.9 years, 176.1 ± 11.6 cm, 71.2 ± 9.4 kg, skinfold thickness: 5.93 ± 0.8 mm, VO_{2Peak}: 43.3 ± 4.1 $mL.kg^{-1}min^{-1}$, W_{Peak}: 177.1 ± 29.9 W) were included in the final analyses. All participants were physically active but not specifically trained in cycling. Participants were eligible for the study if they were free of acute infections, injuries, chronic diseases, recent medication intake, or any restrictions that could have influenced the test. The study was approved by the local ethics committee (GZ. 39/132/63 ex 2022/23) and conducted in accordance with the Declaration of Helsinki.

2.2 Experimental design

Participants performed one maximal single-leg step incremental cycling test. They were instructed not to perform any strenuous exercise within 24 h before the test. On the test day, following the signing of the written informed consent, anthropometric measurements were recorded and the electromechanically braked cycle ergometer (Excalibur Sport, Lode, Groningen, Netherlands) was individually adjusted to the participant. The single-leg incremental cycling test was performed with the right leg in all participants. To enable a safe and easy execution of the test, the left pedal was demounted. The incremental protocol to exhaustion started with a 3-minute rest period followed by a 5-minute warm-up at 40 W. Subsequently, the load was stepwise increased by 10 W· $min^{-1}$and ended when the participants could not sustain the load any longer with a cadence of approximately 80 revolutions per minute. The test ended with a 3-minute cool-down period at 40 W followed by a 3-minute rest period. The cycle ergometer and the spirometry were electronically synchronized while sEMG and NIRS were manually synchronized with the rest of the devices by pushing the start button at the beginning of the measurements. Possible asynchronies should be clearly below 1 s and therefore irrelevant for the aim of the study.

2.3 Cardiopulmonary measurements

Expired air was continuously measured during the test with a breath-by-breath system (Metamax 3B, Cortex Biophysic Gmbh, Leipzig, Germany). The spirometer was calibrated according to the manufacture's guidelines on every test day. Raw data was exported as excel CSV in 5 s intervals via Metasoft Studio software (Cortex Biophysic Gmbh, Leipzig, Germany). Heart Rate (HR) was measured using a chest strap (H10, Polar Electro, Kempele, Finnland) which was connected to the spirometer via Bluetooth signal.

2.4 Near-infrared spectroscopy

Relative changes in deoxygenated haemoglobin + myoglobin (m[HHb]) were measured at 10 Hz by a continuous wavelength portable NIRS device (PortaMon, Artinis Medical Systems, Elst, Netherlands) (Barstow, 2019). Positions for the NIRS sensors were at 1/3 the distance from the proximal pole of the patella to the greater trochanter (van der Zwaard et al., 2016). Prior to placing the NIRS sensors, adipose tissue thickness was measured with ultrasound (Esaote Mylab 60, Esaote SpA, Genova, Italy). The skin was then shaved and cleansed with alcohol. The NIRS sensors were wrapped in transparent foil to protect them from sweat and were attached with tape to the leg. Furthermore, a light-absorbing black cloth and elastic bandages were then wrapped around the thigh to shield the sensors from ambient light.

2.5 Electromyography

Muscle activity was assessed using sEMG (Ultium EMG System, Noraxon Inc., Scottsdale, AZ, United States) recording at a sampling rate of 2000 Hz (MR3 software version 3.18.64, Noraxon Inc., Scottsdale, AZ, United States). The sEMG electrodes were placed as close as possible proximally to the NIRS device, and ultrasound imaging was used to ensure that the electrodes were positioned on the VL muscle. Following established methodology (Hermens et al., 2000), the skin was prepared properly before electrode placement, including shaving, abrasion with sandpaper, and thorough cleansing with alcohol to optimize impedance conditions for accurate sEMG signal measurements. To minimize the risk of detachment during movement, the sEMG sensors were securely attached to the leg using double-sided adhesive tape under and strips over the sensors, while ensuring that the cables leading to the electrodes were not impeded.

2.6 Data analysis

2.6.1 Systemic variables

Based on the actual standard three-phase two threshold model of energy supply (Skinner and Mclellan, 1980; Binder et al., 2008), two breakpoints were determined from an incremental protocol to exhaustion. Using respiratory parameters, the first ventilatory threshold/breakpoint (VT_1), as well as the second ventilatory threshold/breakpoint (VT_2), which is equal to the respiratory compensation point (RCP), were determined according to Beaver et al. (1986), Wasserman et al. (1994), and Binder et al. (2008). VT_1 was defined as the first increase of VE accompanied by an increase in $\dot{V}E/\dot{V}O_2$ without an increase in $\dot{V}E/\dot{V}CO_2$. VT_2 respectively RCP, which was used for further analyses, was determined by an increase in both the respiratory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$) and for carbon dioxide ($\dot{V}E/\dot{V}CO_2$) accompanied by the second sharp increase in $\dot{V}E$ detected by means of multi-linear regression analysis using Vienna CPX-Tool (https://www.univie.ac.at/vcpx/), a commercially available software. The region of interest for determination of RCP was set between the first threshold/breakpoint (approximately 40% of peak power output) and peak power output (W_{peak}) which denotes the highest power output pedaled for at least 30 s in the incremental test. The highest VO_2 value averaged over a 30 s period at W_{peak} represented $\dot{V}O_{2peak}$. Since the specific one-leg exercise modality did not allow a maximum systemic exhaustion, and since the determination of VO_{2max} was not targeted in this investigation, the termsVO_{2peak} and W_{peak} were used.

2.6.2 Local muscle variables

Sample rate and the noise of the m[HHb] NIRS signal was reduced by a factor of 50 using a lowpass Chebyshev Type I infinite impulse response filter of order 8. Root mean square (RMS) of the raw sEMG signals were calculated using a sliding window of 1,000 points corresponding to a window duration of 9.5 s. Subsequently, the sample rate and the noise of the sEMG signals was reduced by a factor of 1,000 using a lowpass Chebyshev Type I infinite impulse response filter of order 8. Then, a two-line regression (Osawa et al., 2011; Boone et al., 2016a) was employed for both NIRS and sEMG data to determine a possible breakpoint ($m[HHb]_{BP}$, EMG_{BP}) with the lowest overall root mean square error. As artefacts were observed at the beginning and the end of the measurements, the first 3 minutes when workload started to increase and the last 2 minutes of the data before maximal workload was reached were not included. Furthermore, the region of interest to determine the breakpoint was limited to 40%–90% of peak power output. A 50-fold resampling strategy to ensure the robustness and objectivity of the detected breakpoints was used. Specifically, 80%of the data set was randomly sampled to estimate the breaking point in each fold. The mean value of the breaking points from these folds provides a robust and objective estimate of the physiological breakpoints.

2.7 Statistical analysis

Means, standard deviations, and 95% confidence intervals were calculated for all variables. A Shapiro-Wilk test was used to test for normal distribution and a Mauchly-test was used to test for sphericity. Power output data was normally distributed (p = 0.16–0.95 for different variables) but sphericity was violated ($p <$ 0.01), therefore, a Greenhouse-Geissler correction was applied for the repeated measures analysis of variance to compare all the means (RCP, EMG_{BP} and $m[HHb]_{BP}$) of the locomotor (right vastus lateralis) and non-locomotor (left vastus lateralis) muscles. Pearson correlation coefficients were computed to evaluate the linear relationship between the power output values at which the

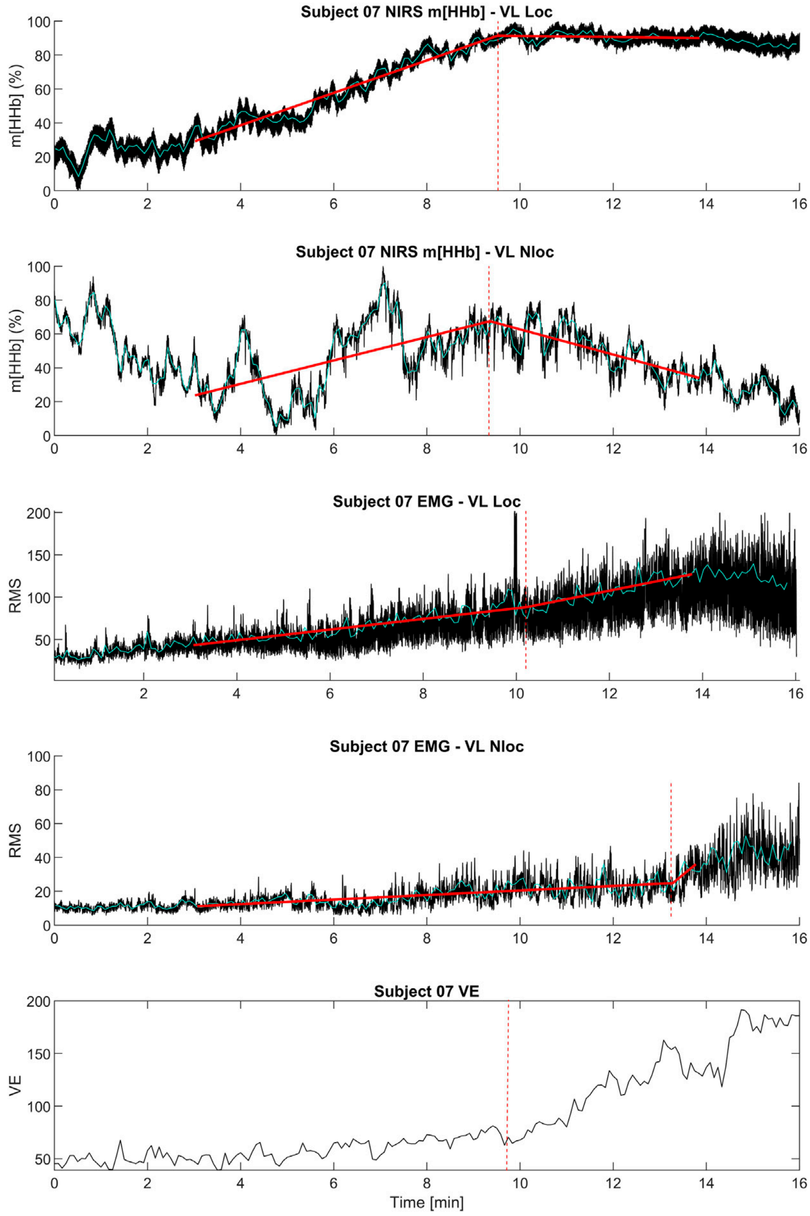

FIGURE 1
Exemplary data set of an individual subject including the kinetics of ventilation ($\dot{V}E$), and the locomotor (Loc) and non-locomotor (Nloc) vastus lateralis (VL) NIRS (HHb) and EMG (RMS) signals during the step-incremental single-leg cycling. Black lines show original data, cyan lines show filtered data, red lines show linear regressions. Vertical dashed red lines show breakpoints. Please note that HHb kinetics of the non-locomotor vastus lateralis does not represent a typical behavior as m[HHb] increased or decreased close to RCP in the different participants.

breakpoints occurred across the variables. According to Cohen (1988), the magnitude of correlations was assessed as small, medium, and strong for r = 0.10, r = 0.30, and r = 0.50, respectively. Furthermore, intraclass correlation coefficients (ICC(3.1)) were computed between breakpoints to assess the agreement between breakpoints. Bland-Altman analysis (Bland and Altman, 1986), mean absolute difference, and regression intercepts were used to assess agreement in power output between the breakpoints. All tests were performed with SPSS 29 and the level of significance was set to 0.05.

3 Results

3.1 Locomotor muscle

The m[HHb] signal in the working muscle (locomotor vastus lateralis) showed a consistent pattern that increased from the start and attenuated (or decreased) at about 75% of peak power output (W_{Peak}). The sEMG (RMS) signal of the working muscle initially increased with increasing work rate, demonstrating a distinct change in slope close to the RCP. However, this change in slope was not

TABLE 1 Absolute and relative power values and absolute VO_2 and HR values at the respiratory compensation point as well as $m[HHb]_{BP}$ and EMG_{BP} of the locomotor and non-locomotor muscles.

	Power at breakpoints (W)		% of W_{peak} (%)		VO_2 at breakpoints (L/min)	HR at breakpoints (bpm)
	Mean ± SD (CI, 95%)	Range	Mean ± SD (CI, 95%)	Range	Mean ± SD (CI, 95%)	Mean ± SD (CI, 95%)
RCP	127.3 ± 21.8 (113.5, 141.2)	94.6–167.5	71.9 ± 1.9 (64.1, 79.8)	68.1–74.5	2.24 ± 0.4 (1.99, 2.49)	161.5 ± 15 (151.8, 171.2)
m[HHb] (VL, Loc)	119.7 ± 23.6 (104.6, 134.7)	91.4–154.9	67.6 ± 6.7 (59.1, 76.1)	58.1–80.3	2.11 ± 0.4 (1.87, 2.36)	158.8 ± 14 (149.9, 167.8)
m[HHb] (VL, Nloc)	117.5 ± 17.9 (106.1, 128.8)	93.2–156.4	66.9 ± 7.2 (60.4, 73.3)	55.0–78.2	2.16 ± 0.3 (1.97, 2.36)	158.1 ± 12 (150.6, 165.5)
EMG (VL, Loc)	126.6 ± 26.0 (110.2, 143.1)	88.1–171.1	71.3 ± 5.6 (62.1, 80.6)	59.8–81.5	2.22 ± 0.4 (1.95, 2.49)	162.0 ± 15 (152.3, 171.8)
EMG (VL, Nloc)	126.1 ± 28.4 (108.1, 144.2)	88.6–179.5	70.9 ± 7.4 (60.8, 81.1)	58.0–81.5	2.25 ± 0.5 (1.95, 2.56)	162.2 ± 13 (154.0, 170.5)

Data are presented as mean ± SD, w_{peak} peak power; HR, heart rate; SD, standard deviation; RCP, respiratory compensation point; Loc, locomotor muscle, Nloc non-locomotor muscle; VL, vastus lateralis.

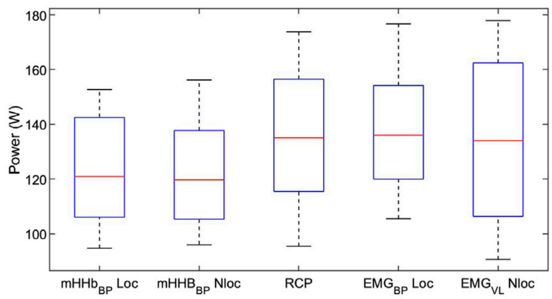

FIGURE 2
Mechanical power at breakpoints of different variables. Note that there was no significant difference between the breakpoints (boxes show the range of the central 50% of data, red lines display the medians, whiskers display minimum and maximum values of data).

always an increase but in some cases a decrease in slope. Figure 1 shows a representative data set from an individual.

Table 1 shows the occurrence of the different breakpoints in W and as percentage of peak power output reached during the single-leg exercise. Furthermore, it shows the absolute values of VO_2 and heart rate at breakpoints.

Repeated measures analysis of variances with Greenhouse-Geiser correction indicated that there was no significant difference between power output values at RCP and breakpoints of the m[HHb] and sEMG responses of the locomotor and non-locomotor vastus lateralis, $F\ (3.0,33.4) = 1.53$, $p = 0.23$, $\eta^2p = 0.122$ (see Figure 2). Figure 3 presents Bland-Altman plots displaying the agreement between power output at RCP, $m[HHb]_{BP}$, and EMG_{BP} of the locomotor vastus lateralis. The mean average difference between RCP and $m[HHb]_{BP}$ was 7.7 W (limits of agreement (LoA): lower = −12.8 W, higher = 28.1 W) with a mean absolute difference of 10.2 ± 7.7 W. The mean average difference between RCP and EMG_{BP} was 0.67 W (LoA: lower = −22.1 W, higher = 23.4 W) with a mean absolute difference of 8.8 ± 7.1 W. The mean average difference between $m[HHb]_{BP}$ and EMG_{BP} was 7.0 W (LoA: lower = −32.5 W, higher = 46.5 W) with a mean absolute difference of 16.7 ± 12.5 W.

Power output values of RCP and all breakpoints determined from the locomotor vastus lateralis correlated significantly with each other (all $p < 0.01$). The correlation coefficients were r = 0.67 (0.16, 0.90) ($m[HHb]_{BP}$ VL loc vs. EMG_{BP} VL loc), r = 0.90 (0.67, 0.97) ($m[HHb]_{BP}$ VL Loc vs. RCP), and r = 0.90 (0.66, 0.97) (RCP vs. EMG_{BP} VL Loc). Intraclass correlation coefficients (ICC(3.1)) were ICC = 0.80 (0.34, 0.94) ($m[HHb]_{BP}$ VL loc vs. EMG_{BP} VL loc), ICC = 0.92 (0.63, 0.98) ($m[HHb]_{BP}$ VL Loc vs. RCP), and ICC = 0.94 (0.80, 0.98) (RCP vs. EMG_{BP} VL Loc). The relationships between the RCP as well as $m[HHb]_{BP}$ and EMG_{BP} from the locomotor VL are shown in Figure 4. Bias assessed as regression intercepts were not significant (Table 2).

Similar to power output values, repeated measures ANOVAs revealed that there was no significant difference between RCP, $m[HHb]_{BP}$, and EMG_{BP} in VO_2 ($F\ (4,44) = 0.53$, $p = 0.71$, $\eta^2p = 0.046$) and heart rate ($F\ (4,44) = 1.01$, $p = 0.414$, $\eta^2p = 0.084$). For detailed results on heart rate and VO_2 data, please see supplement.

3.2 Non-locomotor muscle

In contrastto the locomotor muscle, the non-locomotor muscle did not show such a consistent pattern in the m[HHb] signal. Here, the m[HHb] showed greater fluctuation with both increases or decreases after the RCP. The sEMG (RMS) signal of the non-locomotor muscle showed much lower absolute values and, similar to the non-locomotor m[HHb] signal, an inconsistent pattern (see Figure 1).

The $m[HHb]_{BP}$ and EMG_{BP} from the non-locomotor muscle also correlated significantly, but not as strong, with RCP (r = 0.66 (0.13, 0.89)/ICC = 0.74 (0.16, 0.92), r = 0.77 (0.36, 0.93)/ICC = 0.90 (0.63, 0.97), respectively). Furthermore, there was a significant correlation between $m[HHb]_{BP}$ and EMG_{BP} of the non-locomotor muscle with r = 0.86 (0.55, 0.96)/ICC = 0.79 (0.31–0.94).

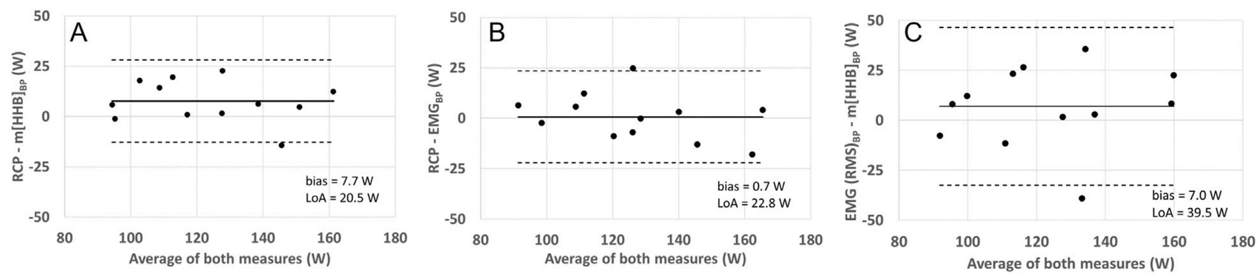

FIGURE 3
Bland-Altman plots displaying agreement between power (W) corresponding with RCP and VL loc m[HHb] **(A)**, RCP and VL Loc EMG BP **(B)**, and VL Loc EMG BP and VL Loc m[HHb] **(C)**. The horizontal solid line represents the mean difference and the horizontal dashed line the 95% limits of agreement.

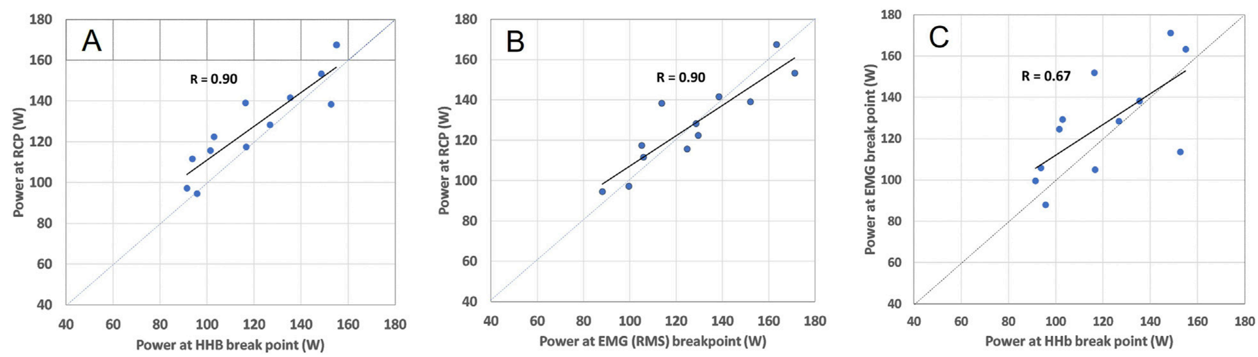

FIGURE 4
Relation between $m[HHb]_{BP}$ and RCP **(A)**, EMG_{BP} and RCP **(B)**, and $m[HHb]_{BP}$ and EMG_{BP} **(C)** in the locomotor VL including respective Pearson correlation coefficients. The dashed lines represent the line of identity.

TABLE 2 Pearson correlation coefficients, intraclass correlation coefficients, and power differences between breakpoints. Means (CI, 95%)/± SD.

	Correlation coefficient	ICC (3.1)	Bias/regression intercept [W]	LoA [W]	MAD [W]
RCP vs. $m[HHb]_{BP}$	r = 0.90 (0.67, 0.97) ($p < 0.01$)	ICC = 0.92 (0.63, 0.98) ($p < 0.01$)	28.3 ± 15.7 (p = 0.10)	7.7 (−12.8, 28.1)	10.2 ± 7.7
RCP vs EMG_{BP}	r = 0.90 (0.66, 0.97) ($p < 0.01$)	ICC = 0.94 (0.80, 0.98) ($p < 0.01$)	32.0 ± 15.2 (p = 0.06)	0.67 (−22.1, 23.4)	8.8 ± 7.1
$m[HHb]_{BP}$ vs EMG_{BP}	r = 0.67 (0.16, 0.90) ($p < 0.05$)	ICC = 0.80 (0.34, 0.94) ($p < 0.01$)	38.1 ± 31.2 (p = 0.25)	7.0 (−32.5, 46.5)	16.7 ± 12.5

LoA, Level of Agreement (Bland Altman), ICC, intraclass correlation coefficient; MAD mean absolute difference.

4 Discussion

Several studies compared a systemic breakpoint with local muscle breakpoints derived from both NIRS and sEMG signals (Osawa et al., 2011; Racinais et al., 2014; Boone et al., 2016a; Iannetta et al., 2017; Inglis et al., 2017; Goulding et al., 2021; Caen et al., 2022). This study expands on previous research by including local muscle breakpoints from both the locomotor muscle and the contralateral non-locomotor muscle. As hypothesized, strong correlations between systemic breakpoints (RCP) and local muscular EMG_{BP} and $m[HHb]_{BP}$ in the locomotor muscle (r = 0.90, ICC = 0.92–0.94) were observed with no significant differences between the power output at breakpoints. Although breakpoints were not significant different, substantial mean absolute difference values between systemic and local breakpoints (8.8–10.2 W) were observed. In the contralateral non-locomotor muscle, both $m[HHb]_{BP}$ and, in contrast to our expectations, also EMG_{BP} correlated significantly with systemic RCP. However, correlation between breakpoints was smaller in the non-locomotor muscles (r = 0.66–0.77, ICC = 0.74–0.90) than in the active, main locomotor muscle. Also, in non-locomotor muscle no significant differences were observed between breakpoints.

4.1 Locomotor muscle

During an incremental exercise, an increasing number of motor units (from Type I → Type IIa → Type IIx) are recruited in the locomotor muscle (Henneman, 1957). This can be observed in the sEMG signal by an increased amplitude which further increases when type IIx fibers are recruited (EMG_{BP}). Within the muscle, O_2 extraction increases, leading to a decrease in m $[O_2Hb]$ and an increase in m[HHb]. With progressive recruitment of Type II fibers, it appears that O_2 extraction reaches its limits and a plateau occurs in m[HHb], which allows to detect a $m[HHb]_{BP}$ (Boone et al., 2016b). Furthermore, the progressive recruitment of motor units induces metabolic acidosis including H+ and lactate production in the muscle which will be transported to the blood system. The decrease of pH level from H+ will increase ventilation to maintain the acid-base balance which can be observed by the second inflection of the linear increase in ventilation at RCP (Wasserman et al., 1994).

When comparing systemic RCP and local muscle breakpoints for EMG_{BP} or $m[HHb]_{BP}$, our results in the locomotor muscle (VL right leg) align with prior studies on cycling that demonstrated a strong correlation (Racinais et al., 2014; Boone et al., 2016a; Iannetta et al., 2017; Goulding et al., 2021). The correlation magnitudes in our study were similar or slightly lower to earlier findings. While we found a correlation between RCP and EMG_{BP} of r = 0.90, others reported correlations as high as 0.97 (Iannetta et al., 2017). The correlation between RCP and NIRS breakpoints with r = 0.90 was higher than r = 0.57 reported by (Racinais et al., 2014) but similar to other reported r-values ranging between 0.90–0.96 (Boone et al., 2016a; Goulding et al., 2021). As reported in the review by Sendra-Pérez et al. (2023), high relationships are also observed in other muscles (e.g., gastrocnemius) and different types of movements (e.g., running or rowing) with a combined intraclass correlation coefficient of 0.80 between NIRS breakpoints (based on muscle oxygen saturation SmO_2) and the 2nd ventilatory breakpoint.

In the present study, no significant differences between RCP and the local breakpoints were observed. However, differences in the occurrence and sequence of breakpoints across studies remain heterogeneous in the literature. For instance, some researchers reported that EMG breakpoints were detected earlier than RCP and NIRS breakpoints, with no significant differences among the latter (Boone et al., 2016a; Goulding et al., 2021). Conversely, other studies detected EMG breakpoints significantly later than both NIRS breakpoints and RCP (Osawa et al., 2011; Racinais et al., 2014). Moreover, in accordance to the present study, Iannetta et al. (2017) reported no difference between the three types of breakpoints.

This variability in breakpoints can partly be attributed to differences in the experimental protocol, such as with single-leg versus classic cycle ergometer tests, and data analysis methods. For example, some studies employed an individual Mean Response Time (MRT), adjusting for the delay in local metabolic responses reaching pulmonary circulation, i.e., the onset of $\dot{V}O_2$ after the onset of the incremental test (Fontana et al., 2015; Caen et al., 2018). This time duration is often used to align NIRS and EMG data with $\dot{V}O_2$ data inducing breakpoint upward shifts of 41–44 s (Boone et al., 2016a; Caen et al., 2022) towards RCP. Although we did not observe a significant difference in our data, $m[HHb]_{BP}$ occurred 7.7 W earlier than RCP, which corresponds to approx. 46 s, similar to previously reported MRT values.

Furthermore, the methods for determining breakpoints varied, from visual inspection of RCP (Racinais et al., 2014; Boone et al., 2016a; Iannetta et al., 2017) to semi-automated methods utilized in this study. In addition, we modelled sEMG data kinetics with a two-line regression in accordance to Osawa et al. (2011) and Boone et al. (2016a) but in contrast to others (Hug et al., 2003; Iannetta et al., 2017) who account for a first and second EMG breakpoint. To summarize, while there is a strong underlying physiological mechanism shared across studies, the results are not interchangeable due to methodological differences and variations in experimental protocols.

4.2 Non-locomotor muscle

The presence of physiological breakpoints in non-locomotor muscles offers intriguing insights into the mechanistic relationship between local and systemic physiological response to exercise with increasing workload. However, although meaningful $m[HHb]_{BP}$ and EMG_{BP} could be detected in all participants, the kinetics of m[HHb] and EMG was not as consistent in the non-locomotor compared to the locomotor muscles. This was probably due to different activation patterns in the different participants of which some showed clear muscle activity in the non-locomotor muscle, e.g., to maintain stability on the ergometer. Therefore, m[HHb] sometimes increased (in 7 out of 12 participants), attenuated (1), or decreased (4) close to the RCP. This inconsistency was similar in the sEMG kinetics, however, not directly related to m[HHb].

The presence of a NIRS breakpoint in a non-locomotor muscle can be explained by several mechanisms which may lead to opposing effects in the m[HHb] signal: 1. A systemic increase of blood flow in the non-locomotor (Tanaka et al., 2006) might increase O_2 delivery and therefore decrease m[HHb]. 2. The re-distribution of blood flow during exercise favoring working muscles, respiratory muscles, and the brain would lead to a decrease in O_2 delivery and therefore increase m[HHb] (Ogata et al., 2004). 3. The changes in HHb concentration from the locomotor (and respiratory) muscles are transported via the systemic blood flow to the non-locomotor muscle (Özyener et al., 2012; Yogev et al., 2022; Sendra-Pérez et al., 2024a). Hence, the m[HHb] might show a similar behavior as in the locomotor muscle. Close to the RCP this could lead to an attenuation or even a decrease of m[HHb]. 4. NIRS breakpoints could be attributed to the minor yet increasing muscle activity needed to stabilize the body's position through co-contraction. For instance, during single-leg cycling, the contralateral leg's muscles might not be directly involved in the pedaling action but play a crucial role in maintaining stability and distributing load, which could lead to changes in activity and would also lead to an increase m[HHb]. This was already hypothesized by several authors (Özyener et al., 2012; Yogev et al., 2022; Sendra-Pérez et al., 2024a) but muscle activity was not tested because of the lack of EMG measurements in these studies. In the present study, we could clearly observe co-contraction in the sEMG-data of the non-locomotor muscles (see also Figure 1). Although absolute sEMG values were much lower compared to those of the locomotor muscle, muscular activation that increased with increasing workload was present. This result contrasted findings from Tanaka et al. (2006) who did not observe any sEMG activity on the non-working muscle and was

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therefore not anticipated in our experiment. The minor but consistent activation of the non-locomotor muscles in the present study also led to the non-expected occurrence of EMG breakpoints which were significantly related and not different to RCP or other breakpoints. Hence, our hypothesis that non-locomotor muscles will not show EMG breakpoints must be rejected due to the reasons explained. Therefore, our results cannot augment the physiological framework by Boone et al. (2016a) by non-locomotor muscles yet. However, for future studies, we recommend to better control the activity of non-locomotor muscles.

4.3 Practical applications and physiological mechanism

The use of local breakpoints derived by NIRS (Murias et al., 2013), sEMG (Hug et al., 2003), or both (Iannetta et al., 2017) to estimate systemic breakpoints as a marker between heavy and severe exercise intensity has been studied extensively. While a general relationship with strong correlations has been shown consistently, a high degree of individual variability with large limits of agreement between the breakpoints suggest that systemic and local breakpoints should not be used interchangeably. This is supported by findings that a) training induced changes in systemic breakpoints (RCP) were not related to changes in NIRS breakpoints (Caen et al., 2018; Caen et al., 2022) and b) NIRS breakpoints from the same muscle differed between exercises in different body positions (Goulding et al., 2021). Our results support these conclusions as we also observed large limits of agreement between the breakpoints. Such results led to an ongoing discussion about a possible mechanistic link between local and systemic breakpoints (Caen and Boone, 2023; Goulding et al., 2023). Based on previous and our findings in the present study, we assume that the mechanistic link between the different breakpoints is the relationship between single muscles and the overall systemic cardio-respiratory and metabolic responses. With increased workload, physiological events like the sequential recruitment of muscle fibers combined with maximal O_2 extraction occur in the working muscle and its effects are then transferred to the (cardio-respiratory and metabolic) system and non-working muscles. A comparison between local and systemic breakpoints is insofar difficult as many different muscles are involved in complex (whole body) movements like running or cycling which cumulatively create a systemic response (Yogev et al., 2022). The contribution of a single muscle to the systemic response is dependent on the activation and the size of a muscle and, therefore, dependent on intermuscular coordination. Although the contribution of bigger muscles to systemic responses should be generally greater than from smaller muscles, even behavior of smaller muscles during single joint movements (Spendier et al., 2020; Tilp et al., 2022) can be observed in systemic measures. During a movement with several (bigger and smaller) muscles involved, these muscles can be activated differently to share the work load. This will lead to very distinct activation patterns which are difficult to anticipate. Some muscles might increase their activation continuously until exhaustion while others might attenuate or decrease their activation at a certain point because other muscles take over their share of load. In the present study, we could observe all different types of sEMG-profiles (increasing, decreasing, attenuating) in the working muscle (VL) close to the power output at RCP.

The described relationship between the behavior of single muscles and systemic response can explain several unclear observations from the literature. Firstly, although the systemic conditions are mostly driven by the metabolic processes of the main working muscles it is not always possible to draw conclusions to single working muscles from systemic measures, especially in complex exercise where several muscles are involved. Systemic measures represent the cumulative effect of several muscles engaged in a specific movement. When these muscles with different sizes display individual local breakpoints at different workloads during a task with increasing effort, their cumulative systemic response may not accurately mirror their individual behavior. Sendra-Pérez et al. (2024a) recently showed nicely the heterogeneity in individual breakpoints from SmO_2 of different muscles (see their Figure 2), although their means from 26 athletes were not significantly different. Conversely, if these muscles display their local breakpoints at the same workload, this breakpoints may coincide with the systemic breakpoint, possibly delayed by the time of the systemic response (Fontana et al., 2015). Hence, local breakpoints from individual muscles may (Snyder and Parmenter, 2009; Sendra-Pérez et al., 2023) or may not (Possamai et al., 2024; Arnet et al., 2025) coincide with systemic boundaries of physiological domains, depending on type of sport and intermuscular coordination. Secondly, training-induced changes in systemic variables (e.g., increase in RCP) must not necessarily be related to changes in local responses of a specific muscle tested as observed, e.g., by Caen et al. (2022). The training-induced improvements are likely related to the structural and functional improvements of several muscles and also related to improved intermuscular coordination. Thirdly, local muscle breakpoints from specific muscles must not necessarily appear at the same instant when determined from similar exercises in different positions. Goulding et al. (2021) observed different NIRS breakpoints during cycling in a sitting or supine position and they concluded due to their observation that RCP and NIRS breakpoints do not represent the same underlying physiological phenomenon. However, different body positions lead to different muscle lengths and contraction velocities and therefore to favorable or unfavorable contractile conditions for different muscles, therefore to different neuromuscular activation (Hug and Dorel, 2009), probably also depending on the individual anthropometry. Hence, it is not surprising that local breakpoints from a specific muscle show different kinetics in different body positions.

Although local muscular breakpoints cannot be used interchangeably with systemic breakpoints due to the reasons explained above, determining these breakpoints can be of great value. During movements where several muscles are involved, determining local breakpoints from several muscles could help in understanding which muscles are stressed earlier than others and therefore represent a bottleneck for improved performance. Specific training of these muscles could then improve overall performance. Exemplary types of sport would, e.g., be rowing or climbing, where both leg and arm muscles are responsible for overall performance. Furthermore, the effect of athletes' position on different muscles during exercise could be tested to determine efficient movement conditions for specific muscles.

4.4 Limitations

Although an *a priori* power analysis has been performed, the sample with 12 participants including males and females with heterogenous performance levels limits the generalization of results. Furthermore, the results of the breakpoint determination depend crucially on the applied model and model constraints. However, the applied models and constraints are common in the literature. Contrary to our expectations, the non-locomotor muscle exhibited inconsistent activity in stabilizing the movement, thereby impacting the results. Unilateral cycling is very specific exercise which is technically difficult and the test is very much limited by the ability of the participants to pull the pedal up (hip flexor). For similar future experiments we recommend a counterweighted single-leg exercise (Iannetta et al., 2019) or a more isolated exercise as applied by Spendier et al. (2020). In general, the measurement of a single leg could have affected our results as wide limits of agreement in SmO_2 values have been reported between the dominant and non-dominant leg during incremental cycling (Skotzke et al., 2024; Sendra-Pérez et al., 2024b). However, Iannetta et al. (2019) reported no difference in [HHb] breakpoints between the dominant and non-dominant leg during single-leg or counterweighted single-leg exercise.

4.5 Conclusion

In the locomotor muscles, the study revealed strong correlations between systemic breakpoints, particularly the respiratory compensation point (RCP), and local muscle breakpoints derived from both muscular activity (EMG) and oxygenation (NIRS signals). However, high individual variability and substantial absolute differences were observed which indicates that these breakpoints cannot be used interchangeably. Non-locomotor muscles exhibited varying behaviors in the signals, with m[HHb] and sEMG showing inconsistent patterns. However, meaningful m[HHb]BP and EMGBP were detected in non-locomotor muscles and correlated significantly with systemic RCP. These findings emphasize the complexity of the interplay between systemic and local physiological responses during exercise, highlighting the intricate nature of these relationships based on individual muscle coordination.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics committee of the University of Graz. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MT: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. NM: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Software, Writing–original draft, Writing–review and editing. GS-T: Conceptualization, Formal Analysis, Methodology, Software, Visualization, Writing–original draft, Writing–review and editing. AK: Conceptualization, Data curation, Methodology, Writing–original draft, Writing–review and editing. PB: Conceptualization, Data curation, Methodology, Writing–original draft, Writing–review and editing. GT: Conceptualization, Formal Analysis, Methodology, Project administration, Resources, Writing–original draft, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that Generative AI was used in the creation of this manuscript. Throughout the preparation of this work, the authors utilized OpenAI’s ChatGPT to improve readability and refine language, thus assisting in formulating and organizing the content. Subsequently, the authors meticulously reviewed and edited the content as necessary, assuming full responsibility for the publication’s content.

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Supplementary material

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