©Journal of Sports Science and Medicine (2026) **25**, 327-338
http://www.jssm.org DOI: https://doi.org/10.52082/jssm.2026.327

Research article

Comparative Effects of Sand- and Grass-Based Repeated-Sprint Training on Aerobic and Anaerobic Performance in Soccer Players

Hao Yan [1,†], Haiting Zhai [2,3,†], Tingting Wang [1], Duchun Wang [4] and Hongwen Wei [1,5]✉
[1] College of Strength and Conditioning Training, Beijing Sport University, Beijing, China; [2] College of Sports Coaching, Beijing Sport University, Beijing, China; [3] School of Basic Sciences for Aviation, Naval Aviation University, Yantai, China; [4] Chinese Table Tennis Association, Beijing, China; [5] Key Laboratory for Performance Training and Recovery of General Administration of Sport, Beijing Sport University, Beijing, China.
† These authors contributed equally to this work.

Abstract
This randomized controlled trial examined whether repeated-sprint training (RST) performed on sand or grass induces different adaptations in collegiate soccer players. Forty-two male players were randomly assigned to a sand-RST group (SAND, n = 14), a grass-RST group (GRASS, n = 14), or a control group (CON, n = 14). SAND and GRASS performed repeated-sprint training during two scheduled training sessions per week for six weeks, whereas CON completed standard technical soccer training of equivalent duration during the same two weekly sessions. All groups continued the same regular team training program, with the intervention delivered within two scheduled weekly sessions. Before and after the intervention, participants completed vertical jump tests including squat jump and countermovement jump, a running based anaerobic sprint test with peak, mean, and minimum power and fatigue index, and a graded treadmill test providing VO_{2max}, anaerobic threshold, and running economy. Baseline-adjusted analyses were conducted to examine between-group differences (ANCOVA for outcomes meeting model assumptions; mixed-design ANOVA when assumptions were violated). These analyses showed significant Group by Time interactions for all jump and running based sprint variables and for VO_{2max} and anaerobic threshold ($p < 0.01$), whereas the interaction for running economy was not significant ($p = 0.15$). Compared with GRASS, SAND showed greater improvements in squat jump ($p < 0.01$), mean power ($p = 0.03$), minimum power ($p < 0.01$), and fatigue index ($p < 0.01$). Aerobic adaptations were comparable between sand and grass, and no clear surface specific advantage was observed for running economy. In conclusion, implementing RST within scheduled team sessions improved jump performance, repeated-sprint performance indices, and aerobic fitness in collegiate soccer players, while sand-based training may provide greater benefits for squat jump and selected outcomes related to repeated-sprint fatigue resistance.

Key words: Sprint training, sand surface, grass surface, soccer, aerobic capacity, anaerobic capacity.

Introduction

Soccer is a high-intensity intermittent sport that places considerable demands on athletes' energy systems. During a 90-minute match, athletes typically cover 9 to 13 km. Most running and intermittent recovery during matches rely on energy supply from the aerobic system, while explosive movements such as sprinting, shooting, and jumping are mainly dependent on anaerobic metabolism (Arazi et al., 2017; Bangsbo, 1994; Polczyk and Zatoń, 2015; Rampinini et al., 2007). Physiologically, this requires players to possess well-developed aerobic and anaerobic capacities to meet match demands. These demands also vary by playing position. For instance, midfielders perform the highest volume of total running and jogging, wingers engage in the most high-speed running and sprinting, and center backs execute the greatest number of accelerations and decelerations (Kapelman et al., 2022; Modric et al., 2019).

High intensity interval training (HIIT) is widely recognized as an effective strategy to improve these capacities (Arslan et al., 2020; Manuel Clemente et al., 2021; Ndlomo et al., 2023). Among its various modalities, repeated sprint training (RST) is frequently applied and involves short maximal sprints of up to 10 s interspersed with brief recovery periods of up to 60 s (Girard et al., 2011; Leite et al., 2023). RST sessions are relatively short in duration, yet impose substantial physiological stress, eliciting beneficial adaptations in physical function and performance (Gantois et al., 2022; Laakso, 2020; Taylor et al., 2015; Thurlow et al., 2024). Owing to its efficiency and effectiveness, RST has been extensively employed in soccer training programs (Beato et al., 2019; Gatterer et al., 2014; Kavaliauskas et al., 2017; Sanchez-Sanchez et al., 2019).

Maximizing training outcomes within limited training time is a central concern for coaches. When training time is constrained, emphasizing sprint based power development and aerobic conditioning within the same period may involve tradeoffs, and adaptations in one domain may be attenuated. Therefore, optimizing all controllable variables of HIIT becomes crucial. The effectiveness of HIIT can be influenced not only by training content (Brown et al., 2018; Follador et al., 2018; Sindiani et al., 2017) and load characteristics (Beltrami et al., 2021; Gosselin et al., 2012) but also, importantly, by the training surface (Binnie et al., 2013a; Cetolin et al., 2021; Zhang et al., 2024). Different surfaces elicit distinct physiological and biomechanical responses, leading to variations in energy expenditure, kinematics, and muscle activation (Alcaraz et al., 2011; Binnie et al., 2013c; Lejeune et al., 1998; Pinnington and Dawson, 2001a; 2001b; Pinnington et al., 2005; Strydom et al., 1966; Zamparo et al., 1992).

Currently, sand has attracted considerable attention due to its unique physical properties and the accessibility of natural beaches and artificial sand fields worldwide. It

Received: 11 November 2025 / Accepted: 23 January 2026 / Published (online): 01 June 2026

should be noted, however, that sand is not a uniform training medium. Variations in sand type (e.g., grain size), layer depth, and moisture content can substantially alter surface behavior and may meaningfully modify the mechanical stimulus and physiological cost of running and sprinting (Binnie et al., 2013a; 2014). For athletes accustomed to training on firm surfaces, the interest in sand-based training stems not only from its inherent properties but also from the novel stimulus it provides as a medium distinct from grass. Applied work in beach soccer and sand-based interval training has already provided sport-specific evidence that repeated high-intensity efforts on sand impose distinct locomotor demands and can elevate internal load relative to firmer surfaces (Castellano and Casamichana, 2010; Scarfone et al., 2015; Binnie et al., 2013a; Cetolin et al., 2021). Specifically, training on sand increases internal load while reducing external mechanical stress (Binnie et al., 2013a; 2013c). Its unstable and compliant surface elevates energy expenditure (Lejeune et al., 1998; Pinnington and Dawson, 2001b; Zamparo et al., 1992), increases lactate accumulation (Binnie et al., 2013a; Pinnington and Dawson, 2001a; Vuong et al., 2023), and enhances lower-limb muscle activation (Pereira et al., 2021; Pinnington et al., 2005). Importantly, although sand-based training induces distinct neuromuscular and biomechanical constraints, existing evidence suggests that some adaptations can transfer to performance assessed on firm surfaces. For example, prior training studies have reported improvements in sprinting and jumping outcomes measured on grass following sand-based conditioning programs (Binnie et al., 2013c; Impellizzeri et al., 2008). A plausible explanation is that the unstable and yielding substrate may require altered force-production strategies and greater stabilizing demands during propulsion, which could translate into improved concentric-oriented output when athletes return to firmer ground. Moreover, its shock absorbing qualities may reduce musculoskeletal loading and lower the risk of soreness and injury (Brown et al., 2017; Impellizzeri et al., 2008; Miyama and Nosaka, 2004; Singh et al., 2014).

Nevertheless, most RST programs are still implemented on firm surfaces such as grass. Firm surfaces reduce energy cost and promote adaptations in the stretch-shortening cycle (SSC) through more efficient use of elastic energy, which is crucial for developing jumping and high-speed running capacity (Arazi et al., 2014; Pereira et al., 2021; 2022). In contrast, the compliant nature of sand surfaces typically leads to a reduction in movement velocity, which may limit neuromuscular adaptations and force production relevant to sport-specific performance (Binnie et al., 2014; Giatsis et al., 2004; Impellizzeri et al., 2008; Pereira et al., 2023a). However, existing research on sand-based training has largely focused on intermittent sprint or jump training modalities (Pereira et al., 2023a; Zhang et al., 2024) while its effects on RST remain unclear. Given these contrasting biomechanical properties, it is still not well understood whether and how the training surface influences the long term adaptive responses to RST in soccer players. Therefore, the present study aimed to investigate and compare the effects of RST performed on sand versus grass surfaces on aerobic and anaerobic capacities in soccer players. We hypothesized that both training modalities would induce significant improvements, but the sand-based group would demonstrate greater enhancements in squat jump height and in indicators related to repeated-sprint fatigue resistance.

Methods

Participants

Forty-two male collegiate soccer players were recruited from a single university team. All participants were competitive players and held an official athlete classification of Level 2 or above under the national athlete grading system. Players were stratified by playing position and then randomly allocated to SAND, GRASS, or CON using a computer generated random number procedure. The allocation sequence was generated by a researcher not involved in testing and group assignments were revealed after baseline assessments were completed. Eligibility criteria included: (i) no musculoskeletal injury in the previous six months; (ii) no exposure to RST during that period; and (iii) prior familiarity with sand-based training to control for potential confounding factors arising from differences in surface. All participants otherwise followed the same regular team training program. The intervention replaced the content of two scheduled weekly sessions. The protocol was approved by the Institutional Review Board of Beijing Sport University, protocol number No. 2024417H, approval date 10 July 2025. Written informed consent was obtained in accordance with the Declaration of Helsinki. Baseline descriptive characteristics are summarized in Table 1.

Study design

This randomized controlled trial lasted nine weeks and comprised a two-week familiarization phase, a one-week testing phase, and a six-week training phase (Figure 1). During familiarization, players completed progressive sessions ranging from low-intensity jogging to high-intensity drills resembling the experimental protocol. Pre- and post-intervention assessments were completed in two sessions at the same time of day. Session one included the squat jump, countermovement jump, and running-based anaerobic sprint test. Session two included the maximal graded treadmill test and was scheduled at least 48 h after session one. However, some residual fatigue from session one may not be fully excluded and should be considered when interpreting aerobic outcomes. The same testing order and inter-session interval were used at pre- and post-testing. Participants were instructed to avoid strenuous exercise for 24 h before each session and to maintain their usual diet and sleep routines.

Training protocol

Each RST session began with a standardized 12-min warm-up consisting of jogging, dynamic stretching, and joint mobility. For six weeks, SAND and GRASS performed RST during two designated team sessions per week, adapted from Thurlow et al. (2023). Each session comprised three sets of six maximal-effort 30m sprints with 30 s recovery between sprints and 4 min rest between sets, resulting in a weekly sprint volume of approximately 1080m.

Table 1. Baseline characteristics of participants (mean ± SD).

Variable	SAND (n = 14)	GRASS (n = 14)	CON (n = 14)
Age (years)	20.1 ± 1.6	19.6 ± 1.4	19.8 ± 1.3
Height (cm)	177.1 ± 3.6	177.9 ± 5.6	175.1 ± 3.4
Body mass (kg)	73.9 ± 5.2	74.0 ± 5.1	73.5 ± 3.4
Training experience (years)	9.6 ± 1.2	9.4 ± 1.1	9.6 ± 1.1
Playing position (F/M/D)	5 / 4 / 5	5 / 4 / 5	5 / 4 / 5

CON, control; F/M/D, forwards/midfielders/defenders.

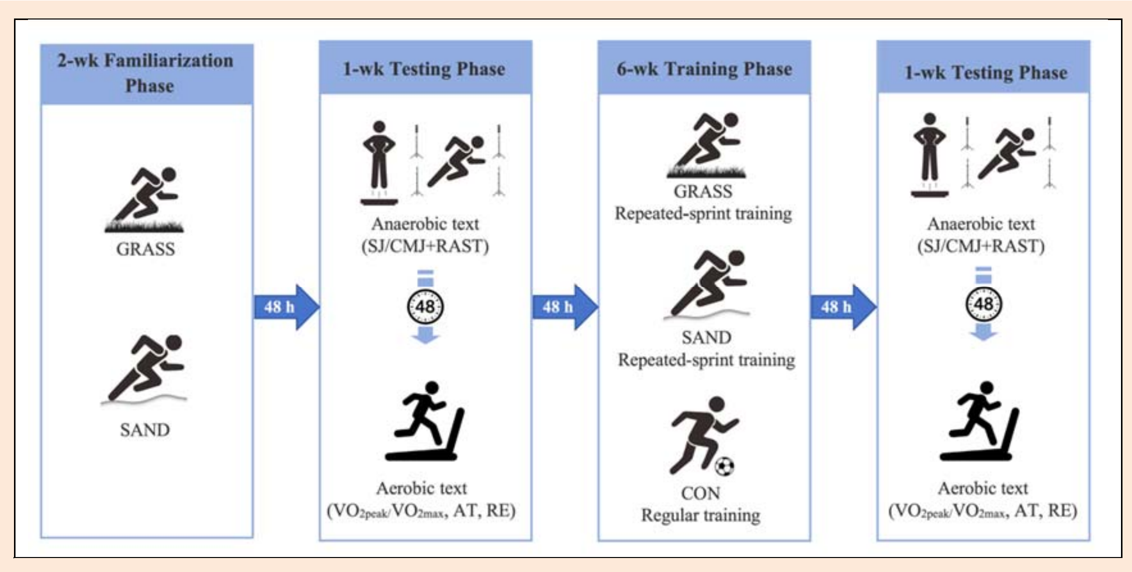

Figure 1. Experimental protocol.

To standardize overall training exposure, CON completed time-matched standard technical soccer training during the same two weekly sessions. All participants otherwise followed the same regular team training regimen throughout the study. Therefore, comparisons with CON reflect the effect of implementing RST in place of time-matched technical training, whereas surface-specific inference is restricted to the direct comparison between SAND and GRASS under an identical sprint structure and volume.

Surface characterization

The mechanical properties of the training surfaces were assessed by measuring peak impact deceleration forces using a 2.25-kg Clegg Impact Hammer (SD Instrument, Suffolk, UK) dropped from a height of 0.457 m. This method is widely used in sport-surface research to quantify surface stiffness, which reflects the resistance to vertical deformation and is inversely related to compliance (Binnie et al., 2013a; 2013c; 2014; Pinnington and Dawson, 2001a; 2001b). In the present study, ten samples were collected randomly across each training area, with an additional ten samples taken from high-use sections to evaluate the characteristics of compacted surfaces. These measurements provide an objective, quantitative comparison of surface stiffness between the SAND and GRASS conditions, thereby aiding in the interpretation of any observed differences in physiological and performance outcomes. The sand surface was an artificial sand field with an approximate sand layer depth of 20 cm. Prior to each training session, the sand was raked and levelled to maintain a consistent running surface, and sessions were conducted under predominantly dry (occasionally variable due to weather) sand conditions. Although the Clegg Impact Hammer provides a standardized index of vertical impact stiffness, it does not directly quantify sand-specific mechanical properties such as depth-dependent deformation or shear resistance, which can also influence energy cost and traction on sand. Therefore, the present measurements should be interpreted as a comparative stiffness indicator rather than a comprehensive characterization of the substrate mechanics.

Performance Tests

Vertical jumping tests

Jumping ability was assessed using squat jump (SJ) and countermovement jump (CMJ) following the protocol of França et al. (2022). For the SJ, players began at ~90° knee flexion, held the position for 3 s, and then jumped vertically. For the CMJ, players performed a rapid downward movement followed by an immediate upward jump. Prior to landing, participants were instructed to maintain an upright trunk and to avoid any deliberate flexion of the lower-limb joints intended to prolong flight time. All jumps were executed on a force platform (Kistler 9281CA, Switzerland; 1000 Hz), with jump height calculated from flight time. All trials were conducted under supervision, and any trial that did not comply with the standardized movement requirements was repeated. Each player performed three trials per jump type with 1-min rest intervals, and the best performance was recorded.

Running-based anaerobic sprint test

Repeated-sprint performance was assessed using the RAST, a validated field test providing indices of sprint power output and sprint decrement across repeated efforts (Nara et al., 2022). Players completed six maximal 35-m sprints with 10-s recovery intervals (Arazi et al., 2017; Garcia et al., 2020). Sprint times were recorded with infrared photoelectric gates (Smartspeed, VALD Performance, Brisbane, Australia). The following variables were derived:

Power = body mass × distance^2 / time^3
Peak power = the highest value among the 6 powers
Minimum power = the lowest value among the 6 powers
Mean power = sum of the 6 power / 6
Fatigue index = (Peak power - Minimum power) / total time of the 6 sprints.

All post-intervention tests were conducted on grass to ensure ecological validity for soccer-specific performance. Importantly, as outlined previously, the neuromuscular adaptations induced by sand-based training has been reported to transfer to sprinting and jumping outcomes assessed on firm surfaces (Binnie et al., 2013c; Impellizzeri et al., 2008). Testing on grass improves ecological relevance for soccer-specific assessment. However, it may also introduce a test-specificity consideration because the SAND group did not perform post-tests on the trained surface. Accordingly, the present design prioritizes transfer to match relevant conditions, and future work should consider dual-surface testing to disentangle training surface and testing surface effects.

Maximal graded treadmill test

Aerobic capacity was assessed by VO_{2max}, anaerobic threshold (AT), and running economy (RE). Tests were conducted on a motorized treadmill (H/P/Cosmos, Pulsar, Nussdorf-Traunstein, Germany). After a 3-min walking warm-up and 5 min jogging at 8 km·h^{-1}, the test began at 10 km·h^{-1} and increased by 2 km·h^{-1} every 3 min until volitional exhaustion (Ziogas et al., 2011).

Heart rate was monitored continuously (Polar H10, Polar Electro Oy, Finland), and respiratory gases were measured with an automated metabolic system (Metalyzer 3B, Cortex, Germany). VO_{2max} attainment was confirmed if ≥ 3 of the following criteria were met (Modric et al., 2020): (a) oxygen uptake plateau (<150 ml·min^{-1} with increasing workload); (b) respiratory exchange ratio ≥1.10; (c) HR > 95% of predicted maximum; (d) volitional exhaustion. Given that a clear plateau is not always observed, VO_{2peak} (highest 30-s value) was recorded, and VO_{2max} is used herein to denote this peak value when plateau criteria were not met.

AT was determined using the V-slope method (Beaver et al., 1986), and RE was calculated as the average oxygen uptake during the final 30 s at 12 km·h^{-1} (Ziogas et al., 2011).

Training Load Monitoring

Heart Rate (HR)

HR was continuously recorded during training using chest-strap sensors (Polar H10, Polar Electro Oy, Finland) paired with a tablet (iPad, Apple Inc., USA). HR_{max} during training was extracted.

Blood Lactate (LA)

Capillary blood samples (20 µL) were collected before training and at 1, 3, and 5 min post-exercise. Samples were stored in microcentrifuge tubes containing 50 µL NaF (1%) and analyzed within 2 h using a biosen analyzer (EKF-Diagnostics GmbH, Magdeburg, Germany). The maximum LA value was recorded.

Rating of Perceived Exertion (RPE)

RPE was measured using the Borg 6–20 scale 30 s before training and 30 min after training.

Statistical analyses

Data are presented as mean ± standard deviation (SD). Normality and homogeneity of variance were checked using the Shapiro–Wilk test and Levene's test, respectively. For all outcome measures, ANCOVA was used as the primary model to examine between-group differences, with the post-intervention value as the dependent variable, group as a fixed factor, and the corresponding baseline value as a covariate. The assumption of homogeneity of regression slopes was tested. For outcomes satisfying this assumption, statistical inference was based on the ANCOVA results, and when a significant main effect of group was found, Bonferroni-adjusted pairwise comparisons were conducted. As a complementary analysis, a 2 (Time) × 3 (Group) mixed-design ANOVA was performed on all outcomes to examine the Time × Group interaction. If a significant interaction was observed, simple-effects analyses were conducted to examine within-group changes over time and between-group differences at each time point. For outcomes that did not meet the ANCOVA assumption, the results from the mixed-design ANOVA and the corresponding post hoc simple effects analyses were primarily relied upon. Effect sizes (Hedges' g) with 95% confidence intervals (CI) were calculated to quantify the magnitude and precision of training effects and interpreted as trivial (≤0.2), small (0.2–0.6), moderate (0.6–1.2), large (1.2–2.0), or very large (≥2.0) (Modric et al., 2020). Statistical significance was set at $p \leq 0.05$. All analyses were performed using SPSS software (Version 24.0, IBM Corp, Armonk, NY, USA).

Results

Ground surface stiffness

Peak impact deceleration forces were significantly lower on SAND compared with GRASS (393.6 ± 70.3 N vs. 1173.0 ± 104.7 N, $p < 0.01$), confirming that GRASS was the firmer surface.

Perceptual and physiological responses to training

During the RST sessions, RPE and LA increased from post warm up to post training on both SAND and GRASS with a significant time effect ($p < 0.01$) as shown in Figure 2. The group by time interaction was not significant for RPE ($p = 0.43$) or LA ($p = 0.22$). HR_{max} during training also did not differ between SAND and GRASS ($p = 0.40$). Collectively, these internal load measures did not indicate a detectable difference between surfaces under the matched repeated sprint protocol.

Jump and repeated-sprint performance

Analysis of covariance results showed that, post-intervention, all jump and repeated sprint variables in SAND and GRASS were significantly higher than those in CON ($p < 0.01$). Additionally, SAND demonstrated significantly

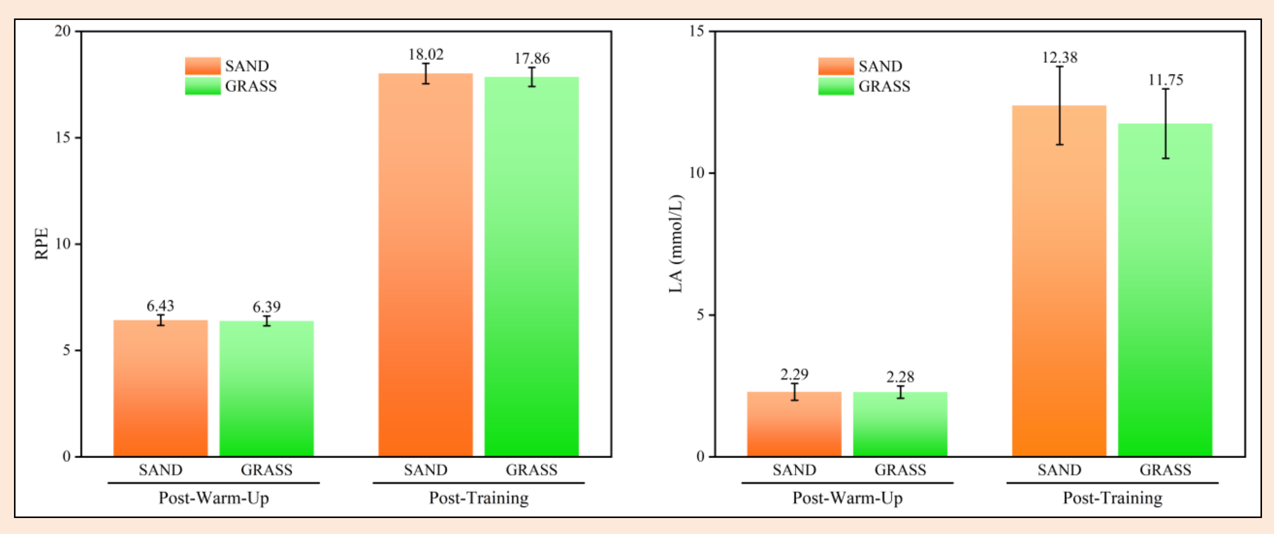

Figure 2. **RPE and LA from post-warm-up to post-training on SAND and GRASS.**

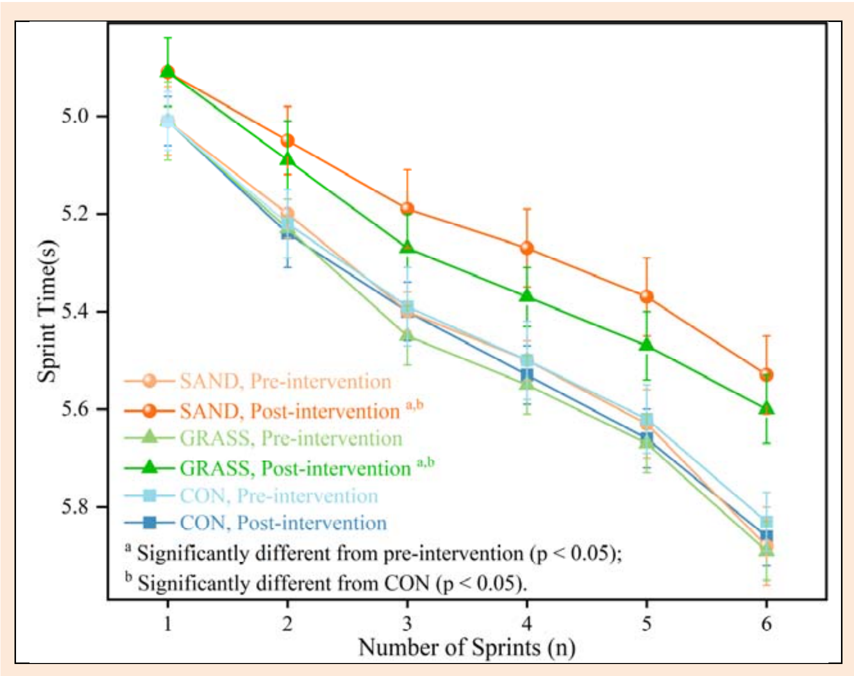

Figure 3. **RAST sprint time before and after intervention in different training groups.**

greater SJ height ($p < 0.01$), minimum power ($p < 0.01$), and mean power ($p = 0.03$) than GRASS, but a significantly lower fatigue index ($p < 0.01$) (Figure 3 and Table 2).

A mixed-design ANOVA revealed significant time × group interactions for all jump and repeated-sprint variables: SJ ($F = 50.7$, $p < 0.01$), CMJ ($F = 43.6$, $p < 0.01$), best sprint time ($F = 40.4$, $p < 0.01$), peak power ($F = 36.1$, $p < 0.01$), minimum power ($F = 136.9$, $p < 0.01$), mean power ($F = 58.3$, $p < 0.01$), and fatigue index ($F = 29.9$, $p < 0.01$). Simple-effects analyses confirmed no significant baseline differences among groups for any performance measure ($p = 0.07–1.00$, ES = -0.52 ~ 0.15). CON showed no statistically significant changes in all jump and repeated sprint variables throughout the training cycle ($p = 0.07–0.88$, ES = -0.25 ~ 0.37), whereas both SAND and GRASS demonstrated significant post-intervention improvements across all variables ($p < 0.01$, ES = -1.87 ~ 2.03). Comparison of group changes revealed that the magnitude of changes in jump and repeated sprint indicators for both SAND and GRASS was significantly greater than that for CON ($p < 0.01$). Compared with GRASS, SAND exhibited a significantly greater magnitude of changes in the indicators of SJ ($p = 0.03$), minimum power ($p = 0.01$), and fatigue index ($p = 0.03$).

Aerobic capacity

Analysis of covariance results indicated that, post-intervention, AT was significantly higher only in the SAND and GRASS compared to the CON ($p < 0.05$). However, since VO_{2max} did not meet the assumption of homogeneity of regression slopes ($p < 0.05$), between-group differences for this variable were examined using a mixed-design analysis of variance followed by simple-effects analyses. These analyses revealed that, post-intervention, VO_{2max} was also significantly higher in both SAND and GRASS than in CON ($p = 0.01–0.02$) (Table 3).

A mixed-design ANOVA revealed significant time × group interactions for VO_{2max} ($F = 8.7$, $p < 0.01$) and AT ($F = 8.0$, $p < 0.01$), but not for RE ($F = 2.0$, $p = 0.15$). Simple-effects analyses confirmed no baseline differences among groups for VO_{2max} (p = 1.00, ES = -0.11 ~ 0.04) or AT (p = 0.41–1.00, ES = 0.16 ~ 0.44). CON exhibited no significant changes in VO_{2max} (p = 0.38, ES = 0.26) or AT (p = 0.49, ES = 0.20) across the training period. In contrast, both SAND and GRASS demonstrated significant post-intervention improvements in VO_{2max} and AT ($p < 0.01$, ES = 1.29 ~ 1.82). The results of the time main effect test showed that RE significantly improved over time ($p < 0.01$, ES = -0.97). Comparisons of relative changes confirmed that the magnitudes of improvement in VO_{2max} ($p < 0.01$) and AT ($p \leq 0.03$) were significantly greater in SAND and GRASS than in CON.

Table 2. Effects of six weeks repeated sprint training on jump and repeated sprint-related variables of college soccer players (mean ± SD).

Variables	Groups	Pre-intervention	Post-intervention	Pre-Post (%)	Interaction effect	Hedges' g (95%CI)
SJ (cm)	SAND	40.8 ± 2.41	43.7 ± 2.19 [a,b c]	6.9 [b,c]	F = 50.7; p < 0.01	2.02 (1.12, 2.91) Very Large↑
	GRASS	40.4 ± 2.46	42.3 ± 2.28 [a,b]	4.7 [b]		1.36 (0.56, 2.16) Large↑
	CON	40.9 ± 2.74	40.6 ± 2.55	-0.8		-0.22 (-0.94, 0.50) Small↓
CMJ (cm)	SAND	44.1 ± 2.46	47.7 ± 2.42 [a,b]	8.2 [b]	F = 44.1; p < 0.01	2.03 (1.14, 2.93) Very Large↑
	GRASS	44.1 ± 2.48	47.0 ± 2.43 [a,b]	6.5 [b]		1.61 (0.78, 2.44) Large↑
	CON	44.4 ± 2.47	43.9 ± 2.63	-1.2		-0.30 (-1.03, 0.42) Small↓
Best sprint time (s)	SAND	5.0 ± 0.07	4.9 ± 0.07 [a,b]	-2.1 [b]	F = 40.4; p < 0.01	-1.58 (-2.41, -0.75) Large↓
	GRASS	5.0 ± 0.09	4.9 ± 0.08 [a,b]	-2.0 [b]		-1.46 (-2.28, -0.65) Large↓
	CON	5.0 ± 0.06	5.0 ± 0.05	-0.03		-0.02 (-0.74, 0.70) Trivial↓
Peak power (w)	SAND	717.2 ± 23.93	762.7 ± 20.94 [a,b]	6.4 [b]	F = 35.3; p < 0.01	1.94 (1.06, 2.82) Large↑
	GRASS	718.4 ± 23.87	758.0 ± 21.19 [a,b]	5.5 [b]		1.67 (0.83, 2.52) Large↑
	CON	715.8 ± 23.94	713.3 ± 24.29	-0.4		-0.11 (-0.83, 0.61) Trivial↓
Minimum power (w)	SAND	445.3 ± 19.70	533.3 ± 20.63 [a,b,c]	19.8 [b,c]	F = 136.9; p < 0.01	1.29 (0.50, 2.09) Large↑
	GRASS	443.6 ± 20.00	511.8 ± 21.29 [a b]	15.4 [b]		1.00 (0.23, 1.77) Moderate↑
	CON	454.5 ± 19.04	446.4 ± 21.97	-1.8		-0.12 (-0.84, 0.60) Trivial↓
Mean power (w)	SAND	571.2 ± 27.01	640.1 ± 21.12 [a,b,c]	12.1[b]	F = 58.3; p < 0.01	1.96 (1.07, 2.84) Large↑
	GRASS	563.3 ± 27.02	616.5 ± 25.28 [a,b]	9.4 [b]		1.51 (0.69, 2.33) Large↑
	CON	571.2 ± 25.75	562.4 ± 25.68	-1.5		-0.25 (-0.97, 0.47) Small↓
Fatigue index	SAND	8.3 ± 0.32	7.3 ± 0.37 [a,b,c]	-12.1 [b,c]	F = 29.9; p < 0.01	-1.87 (-2.74, -1.00) Large↓
	GRASS	8.4 ± 0.42	7.8 ± 0.33 [a,b]	-7.1 [b]		-1.12 (-1.90, -0.35) Moderate↓
	CON	8.0 ± 0.44	8.2 ± 0.45	2.5		0.37 (-0.35, 1.10) Small↑

[a] Significantly different from pre-intervention (p < 0.05); [b] Significantly different from CON (p < 0.05); [c] Significantly different from GRASS (p < 0.05).

Table 3. Effects of six weeks of repeated-sprint training on aerobic capacity variables in collegiate soccer players (mean ± SD).

Variables	Groups	Pre-intervention	Post-intervention	Pre-Post (%)	Interaction effect	Hedges' g (95%CI)
VO_{2max} (ml/kg/min)	SAND	54.5 ± 3.39	58.4 ± 4.23 [a,b]	7.3 [b]	F = 8.7; p < 0.01	1.72 (0.87, 2.57) Large↑
	GRASS	54.3 ± 3.42	58.2 ± 2.50 [a,b]	7.3 [b]		1.72 (0.87, 2.56) Large↑
	CON	54.0 ± 3.05	54.6 ± 2.87	1.1		0.26 (-0.47, 0.98) Small↑
AT (ml/kg/min)	SAND	40.8 ± 2.49	43.9 ± 2.92 [a,b]	7.6 [b]	F = 8.0; p < 0.01	1.82 (0.95, 2.68) Large↑
	GRASS	41.4 ± 2.93	43.7 ± 3.42 [a,b]	5.3 [b]		1.29 (0.50, 2.09) Large↑
	CON	42.4 ± 3.05	42.8 ± 4.11	0.8		0.20 (-0.52, 0.92) Trivial↑
RE (ml/kg/min)	SAND	46.4 ± 4.59	44.7 ± 4.48 [a]	-3.7	F = 2.0; p = 0.15	-0.97 (-1.74, -0.21) Moderate↓
	GRASS	46.8 ± 3.09	45.1 ± 3.29 [a]	-3.6		-0.97 (-1.74, -0.21) Moderate↓
	CON	47.1 ± 3.08	46.9 ± 3.12	-0.4		-0.11 (-0.83, 0.61) Trivial↓

[a] Significantly different from pre-intervention (p < 0.05); [b] Significantly different from CON (p < 0.05).

Discussion

To our knowledge, this is the first randomized controlled trial to compare RST performed on sand and grass in soccer players while evaluating both anaerobic and aerobic outcomes. The findings demonstrated that six weeks of repeated sprint training on either surface improved jump and repeated sprint performance relative to the control condition, supporting the efficacy of this modality for improving jump performance and repeated-sprint performance indices. SAND showed greater improvements in SJ height and in repeated-sprint measures related to sustained power output and fatigue resistance, including minimum power, mean power, and fatigue index. In contrast, CMJ, peak power, and best sprint time did not differ between surfaces. For aerobic capacity, both training surfaces increased VO_{2max} and AT compared with the control condition, and the magnitudes of change were similar between SAND and GRASS. RE improved within both training groups, yet the group by time interaction was not significant, therefore a surface specific effect on RE cannot be inferred from the present data. Importantly, because all groups followed the same weekly schedule and session duration, the primary planned difference was the content and surface of two designated weekly sessions (RST on sand or grass versus time-matched standard technical training). Therefore, surface-specific inference is restricted to SAND versus GRASS, whereas comparisons versus CON reflect the effect of implementing RST in place of technical training within scheduled sessions.

Perceptual and physiological responses

This study also compared the internal load induced by identical RST protocols on SAND and GRASS. No significant differences were detected in RPE, LA, or HR_{max} between surfaces, which indicates comparable systemic cardiometabolic stress during the sessions. These findings align with a body of prior research indicating no significant differences in LA (Binnie et al., 2013b), HR and RPE (Brown et al., 2017; Zhang et al., 2024) between sand and grass surfaces when training is performed at matched intensities. Given the distinct mechanical properties of sand, the observed similarity in physiological response is noteworthy. Possible reasons include the matched external workload in our design or a Type II statistical error associated with the sample size. However, it should be noted that the physiological and biomechanical differences between sand and grass surfaces diminish at faster running speeds (Binnie et al., 2013c). Evidence suggests (Brown et al., 2017; Lejeune et al., 1998; Pinnington and Dawson, 2001a; Pinnington et al., 2005) that as running speed increases, the difference in ground contact time between sand and grass surfaces decreases, leading to a gradual convergence in the observed trends for EC and kinematic parameters. Although running speed was not directly measured, the high-intensity protocol and elevated physiological responses suggest that relatively high running speeds were achieved during the sprints. Because ground contact time, step frequency, and sprint kinematics were not measured, these biomechanical explanations should be considered speculative and based on prior literature rather than direct evidence from the present dataset. Furthermore, variations in surface properties, such as the type of sand or grass, moisture content, and thickness, can modify the resulting stiffness characteristics, thereby eliciting different training stimuli (Binnie et al., 2013a; 2014). Research suggests that a reduced difference in measured peak impact deceleration between sand and grass surfaces may lead to smaller differences in physiological responses across surfaces (Binnie et al., 2013b). In our measurements, the grass surface was approximately 2.98 times stiffer than the sand surface, a ratio slightly lower than some previously reported values of 3.2 to 4 times (Binnie et al., 2013a; Brown et al., 2017; Pinnington and Dawson, 2001a). Therefore, the specific properties of the sand used may also help explain the absence of significant differences in physiological responses between sand- and grass-based training.

More importantly, although performing exercise at the matched same intensity on sand can elicit similar overall physiological response parameters, it induces distinct mechanical and neuromuscular stimuli (Lejeune et al., 1998; Pereira et al., 2021). Therefore, the absence of between surface differences in physiological metrics is interpreted as reflecting comparable systemic demand, whereas the observed differences in repeated sprint outcomes are more likely attributable to surface driven neuromuscular and mechanical constraints rather than uniformly greater internal load on SAND.

Anaerobic capacity and jumping performance

Both SJ and CMJ are widely used to evaluate lower-limb explosive power. CMJ reflects SSC utilization, while SJ isolates concentric strength (McGuigan et al., 2006; Nishioka and Okada, 2022). Given that sprinting involves both SSC efficiency and concentric power generation, RST can indirectly enhance vertical jump performance. Previous studies confirm that RST improves SJ and CMJ through enhanced muscle strength, neuromuscular adaptations, and improved SSC utilization (Buchheit et al., 2010; Gantois et al., 2019; 2022; Thurlow et al., 2024). Consistent with these findings, both SAND and GRASS significantly increased SJ and CMJ in our study, although some research has reported no changes (Michailidis et al., 2022; Soares-Caldeira et al., 2014), possibly due to differences in sport-specific demands or training experience. Additionally, athletes in this study had not previously undergone the same RST protocol, which may have enabled them to achieve greater adaptive improvements.

Notably, the training surfaces elicited differential effects on jump performance improvements. Both the SAND and GRASS exhibited significant increases in SJ and CMJ height compared with the CON ($p < 0.01$). However, the improvement in SJ height was significantly greater in SAND than in GRASS ($p < 0.01$). This difference may be attributed to the instability and compliance of the sand, which reduce ground reaction forces and elastic energy return during running (Pereira et al., 2023b; Zamparo et al., 1992) and induce additional energy loss due to foot slippage in the propulsion phase (Giatsis et al., 2004). Consequently, the lower limb is forced to generate more intense concentric contractions upon take-off, leading to specific physiological adaptations (de Villarreal et al., 2023; Impellizzeri et al., 2008), consistent with previous findings that sand-based training is more effective than grass-based training in enhancing SJ capacity (Ahmadi et al., 2021; de Villarreal et al., 2023; Impellizzeri et al., 2008). In contrast, no significant between-surface differences were observed in CMJ height or its magnitude of improvement, suggesting that CMJ gains likely resulted from general lower-limb strength enhancement induced by sprint training rather than surface-specific mechanical stimuli. Although some studies indicate that SAND impairs SSC utilization (Impellizzeri et al., 2008; Pereira et al., 2023a), our findings, together with prior evidence (Pereira et al., 2021; Pinnington et al., 2005; Mirzaei et al., 2014) have demonstrated that training on sand can elevate activation levels and coordination of lower-limb muscle groups, and augment muscle strength and contractile capacity (Binnie et al., 2014; Mirzaei et al., 2014; Pereira et al., 2021; Pinnington et al., 2005; Zhang et al., 2024), thereby establishing a superior neuromuscular adaptive foundation for vertical jump performance.

Repeated sprint ability and mechanisms of anaerobic adaptation

Both training groups showed marked improvements in RAST outcomes, confirming RST as an efficient method for enhancing anaerobic performance in soccer players. Mechanistically, three processes may explain these adaptations. First, neuromuscular adaptations, including improved motor unit synchronization, increased firing frequency, and enhanced SSC efficiency, contribute to greater explosive power (Buchheit et al., 2010; Gantois et al., 2019; 2022). Second, adaptations in acid-base buffering likely contributed to the observed improvements. The present study demonstrated that both surfaces elicited similarly high lactate concentrations during training (SAND, 12.38 ± 1.38 mmol/L; GRASS, 11.75 ± 1.22 mmol/L). Such a pronounced increase in intramuscular H^+ and lactate is recognized as a key stimulus driving the adaptation of pH regulatory systems (Bishop et al., 2011; Weston et al., 1996). Thus, this common metabolic challenge provides a plausible mechanistic explanation for the enhanced repeated-sprint ability. While it constitutes one contributor to the overall performance gains, it cannot be invoked to explain any potential differences in outcomes between surfaces, especially given that direct markers of acid-base balance (e.g., blood pH, bicarbonate) were not assessed. Third, enhanced energy metabolism efficiency, reflected in greater creatine phosphate and glycogen storage and higher enzyme activity (Michailidis et al., 2022; Taylor et al., 2015), supports improvements in sprint time and mean power.

When comparing surfaces, SAND produced superior improvements in mean and minimum power, as well as fatigue resistance, whereas maximum power and sprint speed did not differ. Although effect sizes for peak power were large within the training groups, the corresponding confidence intervals were relatively wide, indicating limited precision and substantial inter-individual variability. Therefore, peak-power effects should be interpreted cautiously and were not used to support any surface-specific superiority. It should be noted that the fatigue index is ratio-derived. Therefore, the observed reduction in fatigue index may partly reflect the concurrent increase in minimum power rather than an independent physiological adaptation in fatigue resistance. Accordingly, we interpreted fatigue index alongside absolute changes in minimum and mean power. This may be attributed to the direct correlation between peak power and maximum sprint speed, and the already high baseline values of our participants compared with those in previous studies (Maciel et al., 2024; Parnow et al., 2022; Shannon and Carter, 2024), limiting further gains. Therefore, simply changing the training surface was insufficient to elicit significant differences in best sprint time and maximum power between SAND and GRASS. Nonetheless, previous biomechanical work indicates that sprinting on sand can elicit greater lower-limb muscle activation than sprinting on firmer surfaces (Pereira et al., 2021; Pinnington et al., 2005). In addition, the postural adjustments required on an unstable substrate may increase trunk and hip stabilizer demands during running (Pereira et al., 2021). Although such neuromuscular responses were not directly measured in the present study, they provide a plausible explanation for why the sand condition yielded larger improvements in indices reflecting sustained power output across repeated sprints. Future studies incorporating direct measures of trunk and hip activation and sprint kinematics are required to verify whether these mechanisms mediate the observed surface related differences.

Aerobic capacity

VO_{2max}, AT, and RE are key markers of aerobic fitness (Chamari et al., 2005; Metaxas et al., 2005; Nilsson and Cardinale, 2015). Consistent with prior work (Boer and Van Aswegen, 2016; Gantois et al., 2019; 2022), our study confirmed that RST improves VO_{2max}, likely through mitochondrial biogenesis and enhanced enzyme activity (Jacobs et al., 2013; Ross and Leveritt, 2001; Thurlow et al., 2024). Importantly, no differences were observed between surfaces, with nearly identical improvements in VO_{2max} (SAND 7.29% vs. GRASS 7.28%). AT also improved significantly after training, reflecting enhanced buffering and lactate clearance capacity, thereby delaying the point at which lactate accumulation increases disproportionately. Both RST groups (SAND and GRASS) demonstrated greater improvements in AT than the control condition. However, no significant between-surface difference (SAND vs. GRASS) was observed for AT. Studies have shown that sustained high-intensity training provides the optimal stimulus for improving aerobic capacity (Thurlow et al., 2024), while training intervals and short-duration high-intensity exercise may attenuate this stimulus (Boer and Van Aswegen, 2016). Although RST provides sufficient intensity, its brief sprint durations (≤10 s) and short recovery intervals (≤60 s) may have constrained the magnitude of training-induced physiological adaptations. This study found that RE was significantly improved following RST in both the SAND and GRASS. The intrinsic mechanisms underlying this improvement merit further consideration. RE is a multifactorial trait influenced by pulmonary ventilation efficiency, lower-limb kinetics and kinematics, running technique, and neuromuscular characteristics (Barnes and Kilding, 2015; Morgan et al., 1989). RST can simultaneously induce peripheral metabolic adaptations and neuromuscular improvements, such as increased lower-limb strength and enhanced SSC efficiency (Gantois et al., 2019; 2022; Serpiello et al., 2012; Thurlow et al., 2023). However, running biomechanics are established as a critical determinant of RE (Moore, 2016). Therefore, the RE improvement observed in this study is more likely mediated primarily through training-induced neuromuscular adaptations that optimize running mechanics, rather than solely via peripheral metabolic changes. Furthermore, the absence of a significant difference in the magnitude of RE improvement between training surfaces may be attributed to the multifactorial regulation of running biomechanics (Moore, 2016). The single variable of the training surface likely provided insufficient differential stimulation to these key biomechanical factors, resulting in comparable adaptive responses between the two groups.

Several limitations should be noted. First, the sample consisted exclusively of male collegiate soccer players recruited from a single university team, which may limit the generalizability of the findings to other populations (e.g., professional, youth academy, or female players). Second, although the study detected clear training effects relative to the control condition, the sample size may have been insufficient to reliably detect small-to-moderate between-surface differences between the two active training modalities. Therefore, non-significant findings should be interpreted cautiously, as they may reflect limited statistical power and estimate precision rather than true equivalence between surfaces. Third, although session frequency and duration were standardized across groups by design, we did not quantify whole-week external load (e.g., total running distance, high-speed running, or accelerations) across the entire training program. Therefore, residual differences in weekly load distribution cannot be fully excluded. Nevertheless, the intervention replaced two scheduled sessions of equivalent duration within a centrally planned weekly program implemented by the same coaching staff. Fourth, the study did not include direct measurements of key mechanistic variables. Specifically, we did not quantify sand-specific mechanical properties or running biomechanics during training, nor did we collect detailed physiological data, which limits a more complete explanation of the observed adaptations. Finally, only one specific RST protocol was examined, and future investigations should evaluate alternative formats and longer interventions to determine optimal training parameters and surface-specific adaptations.

Conclusion

This study demonstrated that six weeks of RST implemented within scheduled team sessions improved jump performance, repeated-sprint performance indices, and aerobic fitness in collegiate soccer players. Compared with grass, sand-based RST conferred greater benefits that were specific to squat jump performance and indices of repeated sprint fatigue resistance, including higher minimum and mean power and a lower fatigue index, while aerobic improvements were comparable between surfaces.

From a practical perspective, sand may be prioritized when the training objective is to enhance repeated sprint fatigue resistance or to develop concentric power while reducing impact loading. Coaches should weigh these potential benefits against the following limitations: the dissimilarity to competition surfaces, the greater demands on training control and recovery management, and the availability and consistency of sand conditions. Grass remains a pragmatic option when the emphasis is on promoting the transfer of sprint specific mechanics to match conditions or when integration with technical and tactical drills is required. Therefore, we recommend adopting a periodized approach that alternates between sand and grass surfaces in practice, thereby addressing logistical constraints while targeting distinct training adaptations.

Acknowledgements
This work was supported by the Fundamental Research Funds for the Central Universities (Grant No. 2024TNJN003). The datasets generated during the current study are not publicly available but are available from the corresponding author upon reasonable request. The authors declare that they have no conflict of interest. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was carried out. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript.

References

Ahmadi, M., Nobari, H., Ramirez-Campillo, R., Pérez-Gómez, J., Ribeiro, A.L.D.A. and Martínez-Rodríguez, A. (2021) Effects of plyometric jump training in sand or rigid surface on jump-related biomechanical variables and physical fitness in female volleyball players. *International Journal of Environmental Research and Public Health* **18(24)**, 13093. https://doi.org/10.3390/ijerph182413093

Alcaraz, P.E., Palao, J.M., Elvira, J.L.L. and Linthorne, N.P. (2011) Effects of a sand running surface on the kinematics of sprinting at maximum velocity. *Biology of Sport* **28(2)**, 95-100. https://doi.org/10.5604/942737

Arazi, H., Keihaniyan, A., EatemadyBoroujeni, A., Oftade, A., Takhsha, S., Asadi, A. and Ramirez-Campillo, R. (2017) Effects of heart rate vs. speed-based high intensity interval training on aerobic and anaerobic capacity of female soccer players. *Sports* **5(3)**, 57. https://doi.org/10.3390/sports5030057

Arazi, H., Mohammadi, M. and Asadi, A. (2014) Muscular adaptations to depth jump plyometric training: Comparison of sand vs. land surface. *Interventional Medicine and Applied Science* **6(3)**, 125-130. https://doi.org/10.1556/imas.6.2014.3.5

Arslan, E., Orer, G. and Clemente, F. (2020) Running-based high-intensity interval training vs. small-sided game training programs: Effects on the physical performance, psychophysiological responses and technical skills in young soccer players. *Biology of Sport* **37(2)**, 165-173. https://doi.org/10.5114/biolsport.2020.94237

Bangsbo, J. (1994) The physiology of soccer--with special reference to intense intermittent exercise. *Acta Physiologica Scandinavica. Supplementum* **619**, 1-155.

Barnes, K.R. and Kilding, A.E. (2015) Running economy: Measurement, norms, and determining factors. *Sports Medicine - Open* **1(1)**, 8. https://doi.org/10.1186/s40798-015-0007-y

Beato, M., Coratella, G., Bianchi, M., Costa, E. and Merlini, M. (2019) Short-term repeated-sprint training (straight sprint vs. changes of direction) in soccer players. *Journal of Human Kinetics* **70**, 183-190. https://doi.org/10.2478/hukin-2019-0040

Beaver, W.L., Wasserman, K. and Whipp, B.J. (1986) A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology* **60(6)**, 2020-2027. https://doi.org/10.1152/jappl.1986.60.6.2020

Beltrami, F.G., Roos, E., von Ow, M. and Spengler, C.M. (2021) Cardiorespiratory responses to constant and varied-load interval training sessions. *International Journal of Sports Physiology and Performance* **16(7)**, 1021-1028. https://doi.org/10.1123/ijspp.2020-0104

Binnie, M.J., Dawson, B., Pinnington, H., Landers, G. and Peeling, P. (2013a) Effect of training surface on acute physiological responses after interval training. *The Journal of Strength and Conditioning Research* **27(4)**, 1047-1056. https://doi.org/10.1519/JSC.0b013e3182651fab

Binnie, M.J., Dawson, B., Pinnington, H., Landers, G. and Peeling, P. (2013b) Part 2: Effect of training surface on acute physiological responses after sport-specific training. *The Journal of Strength and Conditioning Research* **27(4)**, 1057-1066. https://doi.org/10.1519/JSC.0b013e3182651d63

Binnie, M.J., Dawson, B., Pinnington, H., Landers, G. and Peeling, P. (2014) Sand training: A review of current research and practical applications. *Journal of Sports Sciences* **32(1)**, 8-15. https://doi.org/10.1080/02640414.2013.805239

Binnie, M.J., Peeling, P., Pinnington, H., Landers, G. and Dawson, B. (2013c) Effect of surface-specific training on 20-m sprint performance on sand and grass surfaces. *The Journal of Strength and Conditioning Research* **27(12)**, 3515-3520. https://doi.org/10.1519/JSC.0b013e31828f043f

Bishop, D., Girard, O. and Mendez-Villanueva, A. (2011) Repeated-sprint ability—part II: Recommendations for training. *Sports Medicine* **41(9)**, 741-756. https://doi.org/10.2165/11590560-000000000-00000

Boer, P.H. and Van Aswegen, M. (2016) Effect of combined versus repeated sprint training on physical parameters in subelite football players in South Africa. *Journal of Physical Education and Sport* **16(3)**, 964-971.

Brown, E.C., Hew-Butler, T., Marks, C.R., Butcher, S.J. and Choi, M.D. (2018) The impact of different high-intensity interval training protocols on body composition and physical fitness in healthy young adult females. *BioResearch Open Access* **7(1)**, 177-185. https://doi.org/10.1089/biores.2018.0032

Brown, H., Dawson, B., Binnie, M.J., Pinnington, H., Sim, M., Clemons, T.D. and Peeling, P. (2017) Sand training: Exercise-induced muscle damage and inflammatory responses to matched-intensity exercise. *European Journal of Sport Science* **17(6)**, 741-747. https://doi.org/10.1080/17461391.2017.1304998

Buchheit, M., Mendez-Villanueva, A., Delhomel, G., Brughelli, M. and Ahmaidi, S. (2010) Improving repeated sprint ability in young elite soccer players: Repeated shuttle sprints vs. explosive strength training. *The Journal of Strength and Conditioning Research* **24(10)**, 2715-2722. https://doi.org/10.1519/JSC.0b013e3181bf0223

Castellano, J. and Casamichana, D. (2010) Heart rate and motion analysis by GPS in beach soccer. *Journal of Sports Science and Medicine* **9(1)**, 98-103. https://pubmed.ncbi.nlm.nih.gov/24149392/

Cetolin, T., Teixeira, A.S., Da Silva, J.F., Haupenthal, A., Nakamura, F.Y., Castagna, C. and Guglielmo, L.G.A. (2021) High-intensity intermittent exercise performed on the sand induces higher internal load demands in soccer players. *Frontiers in Psychology* **12**, 713106. https://doi.org/10.3389/fpsyg.2021.713106

Chamari, K., Moussa-Chamari, I., Boussaidi, L., Hachana, Y., Kaouech, F. and Wisløff, U. (2005) Appropriate interpretation of aerobic capacity: Allometric scaling in adult and young soccer players. *British Journal of Sports Medicine* **39(2)**, 97-101. https://doi.org/10.1136/bjsm.2003.010215

de Villarreal, E.S., Rascón, P.B., Becerra, M.O., Calleja-González, J., Alcaraz, P.E., Feito-Blanco, J. and Ramirez-Campillo, R. (2023) Effects of sand surface plyometric and sprint training on physical and technical skill performance in beach handball players. *Journal of Human Kinetics* **90**, 227-237. https://doi.org/10.5114/jhk/169519

Follador, L., Alves, R.C., Ferreira, S.dos S., Buzzachera, C.F., Andrade, V.F.dos S., Garcia, E.D.S.de A., Osiecki, R., Barbosa, S.C. and de Oliveira, L.M. da Silva, S.G. (2018) Physiological, perceptual, and affective responses to six high-intensity interval training protocols. *Perceptual and Motor Skills* **125(2)**, 329-350. https://doi.org/10.1177/0031512518754584

França, C., Gouveia, É., Caldeira, R., Marques, A., Martins, J., Lopes, H., Henriques, R. and Ihle, A. (2022) Speed and agility predictors among adolescent male football players. *International Journal of Environmental Research and Public Health* **19(5)**, 2856. https://doi.org/10.3390/ijerph19052856

Gantois, P., Batista, G.R., Aidar, F.J., Nakamura, F.Y., de Lima-Júnior, D., Cirilo-Sousa, M.S., de Matos, D.G. and Cabral, B.G.A.T. (2019) Repeated sprint training improves both anaerobic and aerobic fitness in basketball players. *Isokinetics and Exercise Science* **27(2)**, 97-105. https://doi.org/10.3233/IES-182212

Gantois, P., Batista, G.R., Dantas, M., de Sousa Fortes, L., da Silva Machado, D.G., Mortatti, A.L. and Cabral, B.G.D.A.T. (2022) Short-term effects of repeated-sprint training on vertical jump ability and aerobic fitness in collegiate volleyball players during pre-season. *International Journal of Exercise Science* **15(6)**, 1040-1051. https://doi.org/10.70252/UXOP1748

Garcia, D., Ramos, I., Pinho, D., Nunes, R., Branco Silva, G.C., Mafra, R. and Melo, G. (2020) The assessment of aerobic capacity and anaerobic power of soccer players of the professional and U-20 categories in Brazilian. *Journal of Exercise Physiology Online* **23(5)**, 37-45.

Gatterer, H., Philippe, M., Menz, V., Mosbach, F., Faulhaber, M. and Burtscher, M. (2014) Shuttle-run sprint training in hypoxia for youth elite soccer players: A pilot study. *Journal of Sports Science and Medicine* **13(4)**, 731-735. https://pubmed.ncbi.nlm.nih.gov/25435763/

Giatsis, G., Kollias, I., Panoutsakopoulos, V. and Papaiakovou, G. (2004) Volleyball: Biomechanical differences in elite beach-volleyball players in vertical squat jump on rigid and sand surface. *Sports Biomechanics* **3(1)**, 145-158. https://doi.org/10.1080/14763140408522835

Girard, O., Mendez-Villanueva, A. and Bishop, D. (2011) Repeated-sprint ability—part I: Factors contributing to fatigue. *Sports Medicine* **41(8)**, 673-694. https://doi.org/10.2165/11590550-000000000-00000

Gosselin, L.E., Kozlowski, K.F., DeVinney-Boymel, L. and Hambridge, C. (2012) Metabolic response of different high-intensity aerobic interval exercise protocols. *The Journal of Strength and Conditioning Research* **26(10)**, 2866-2871. https://doi.org/10.1519/JSC.0b013e318241e13d

Impellizzeri, F.M., Rampinini, E., Castagna, C., Martino, F., Fiorini, S. and Wisloff, U. (2008) Effect of plyometric training on sand versus grass on muscle soreness and jumping and sprinting ability in soccer players. *British Journal of Sports Medicine* **42(1)**, 42-46. https://doi.org/10.1136/bjsm.2007.038497

Jacobs, R.A., Flück, D., Bonne, T.C., Bürgi, S., Christensen, P.M., Toigo, M. and Lundby, C. (2013) Improvements in exercise performance with high-intensity interval training coincide with an increase in skeletal muscle mitochondrial content and function. *Journal of Applied Physiology* **115(6)**, 785-793. https://doi.org/10.1152/japplphysiol.00445.2013

Kapelman, A.E., Kızılet, A. and Bozdogan, T. (2022) The effect of game strategies on the physiological, physical, and technical loads of soccer players. *Annals of Applied Sport Science* **10(1)**, e1014. https://doi.org/10.52547/aassjournal.1014

Kavaliauskas, M., Kilvington, R. and Babraj, J. (2017) Effects of in-season uphill sprinting on physical characteristics in semi-professional soccer players. *Journal of Sports Medicine and Physical Fitness* **57(3)**, 165-170. https://doi.org/10.23736/S0022-4707.16.06066-7

Laakso, L. (2020) Critical evaluation of the physiological adaptations to repeated-sprint training: Implications for training recommendations and repeated-sprint ability of well-trained field-based team-sport athletes. *Journal of Australian Strength and Conditioning* **28(4)**, 75-81.

Leite, C.D.F.C., Zovico, P.V.C., Rica, R.L., Barros, B.M., Machado, A.F., Evangelista, A.L., Leite, R.D., Barauna, V.G., Maia, A.F. and Bocalini, D.S. (2023) Exercise-induced muscle damage after a high-intensity interval exercise session: Systematic review. *International Journal of Environmental Research and Public Health* **20(22)**, 7082. https://doi.org/10.3390/ijerph20227082

Lejeune, T.M., Willems, P.A. and Heglund, N.C. (1998) Mechanics and energetics of human locomotion on sand. *Journal of Experimental Biology* **201(13)**, 2071-2088. https://doi.org/10.1242/jeb.201.13.2071

Maciel, O., Martins, R., Nakamura, F.Y., Figueiredo, P., Afonso, J. and Baptista, I. (2024) The effect of speed endurance versus core training on the repeated sprint ability of youth male soccer players - a randomized controlled trial. *Journal of Sports Science and Medicine* **23(4)**, 907-915. https://doi.org/10.52082/jssm.2024.907

Manuel Clemente, F., Ramirez-Campillo, R., Nakamura, F.Y. and Sarmento, H. (2021) Effects of high-intensity interval training in men soccer player's physical fitness: A systematic review with meta-analysis of randomized-controlled and non-controlled trials. *Journal of Sports Sciences* **39(11)**, 1202-1222. https://doi.org/10.1080/02640414.2020.1863644

McGuigan, M.R., Doyle, T.L., Newton, M., Edwards, D.J., Nimphius, S. and Newton, R.U. (2006) Eccentric utilization ratio: Effect of sport and phase of training. *The Journal of Strength and Conditioning Research* **20(4)**, 992-995. https://doi.org/10.1519/R-19165.1

Metaxas, T.I., Koutlianos, N.A., Kouidi, E.J. and Deligiannis, A.P. (2005) Comparative study of field and laboratory tests for the evaluation of aerobic capacity in soccer players. *The Journal of Strength and Conditioning Research* **19(1)**, 79-84. https://doi.org/10.1519/14713.1

Michailidis, Y., Motsanos, N. and Metaxas, T. (2022) The effects of a repeated sprint ability program on youth soccer players' physical performance. *Trends in Sport Sciences* **29(2)**, 57-63.

Mirzaei, B., Norasteh, A.A., Sáez de Villarreal, E. and Asadi, A. (2014) Effects of six weeks of depth jump vs. countermovement jump training on sand on muscle soreness and performance. *Kinesiology* **46(1)**, 97-108.

Miyama, M. and Nosaka, K. (2004) Influence of surface on muscle damage and soreness induced by consecutive drop jumps. *The Journal of Strength and Conditioning Research* **18(2)**, 206-211. https://doi.org/10.1519/R-13353.1

Modric, T., Versic, S., Sekulic, D. and Liposek, S. (2019) Analysis of the association between running performance and game performance indicators in professional soccer players. *International Journal of Environmental Research and Public Health* **16(20)**, 4032. https://doi.org/10.3390/ijerph16204032

Modric, T., Versic, S. and Sekulic, D. (2020) Aerobic fitness and game performance indicators in professional football players; playing position specifics and associations. *Heliyon* **6(11)**, e05427. https://doi.org/10.1016/j.heliyon.2020.e05427

Moore, I.S. (2016) Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Medicine* **46(6)**, 793-807. https://doi.org/10.1007/s40279-016-0474-4

Morgan, D.W., Martin, P.E. and Krahenbuhl, G.S. (1989) Factors affecting running economy. *Sports Medicine* **7(5)**, 310-330. https://doi.org/10.2165/00007256-198907050-00003

Nara, K., Kumar, P., Rathee, R. and Kumar, J. (2022) The compatibility of running-based anaerobic sprint test and Wingate anaerobic test: A systematic review and meta-analysis. *Pedagogy of Physical Culture and Sports* **26(2)**, 134-143. https://doi.org/10.15561/26649837.2022.0208

Ndlomo, K., Lombard, A. and Green, A. (2023) The effects of high-intensity training on aerobic capacity of football players. *Journal of Physical Education and Sport* **23(9)**, 2291-2299.

Nilsson, J. and Cardinale, D. (2015) Aerobic and anaerobic test performance among elite male football players in different team positions. *LASE Journal of Sport Science* **6(2)**, 73-92. https://doi.org/10.1515/ljss-2016-0007

Nishioka, T. and Okada, J. (2022) Associations of maximum and reactive strength indicators with force-velocity profiles obtained from squat jump and countermovement jump. *Plos One* **17(10)**, e0276681. https://doi.org/10.1371/journal.pone.0276681

Parnow, A., Amani-Shalamzari, S. and Mohr, M. (2022) The repeated curve sprint test appears to be an appropriate tool for estimating anaerobic fitness in young trained male futsal players. *Journal of Human Kinetics* **82**, 181-189. https://doi.org/10.2478/hukin-2022-0044

Pereira, L.A., Boullosa, D., Moura, T.B., Mercer, V.P., Fernandes, V., Bishop, C. and Loturco, I. (2022) Post-activation performance enhancement in sprinters: Effects of hard versus sand surfaces. *Journal of Human Kinetics* **82**, 173-180. https://doi.org/10.2478/hukin-2022-0062

Pereira, L.A., Freitas, T.T., Marín-Cascales, E., Bishop, C., McGuigan, M.R. and Loturco, I. (2021) Effects of training on sand or hard surfaces on sprint and jump performance of team-sport players: A systematic review with meta-analysis. *Strength and Conditioning Journal* **43(3)**, 56-66. https://doi.org/10.1519/SSC.0000000000000634

Pereira, L.A., Freitas, T.T., Zabaloy, S., Ferreira, R.C., Silva, M.L., Azevedo, P.H. and Loturco, I. (2023a) Sprint and jump training on sand vs. grass surfaces: Effects on the physical performance of young soccer players. *The Journal of Strength and Conditioning Research* **37(9)**, 1828-1833. https://doi.org/10.1519/JSC.0000000000004472

Pereira, L.A., Nunes, R.F.H., Freitas, T.T., Paes, C.A., Conde, J.H.S., Novack, L.F., Kosloski, T., Silva, R.L.P., Azevedo, P.H.S.M. and Loturco, I. (2023b) Sand and grass surfaces are equally effective in promoting positive adaptations in the sprint performance of elite young soccer players. *Biology of Sport* **40(4)**, 993-1001. https://doi.org/10.5114/biolsport.2023.123324

Pinnington, H.C. and Dawson, B. (2001a) The energy cost of running on grass compared to soft dry beach sand. *Journal of Science and Medicine in Sport* **4(4)**, 416-430. https://doi.org/10.1016/S1440-2440(01)80051-7

Pinnington, H. and Dawson, B. (2001b) Running economy of elite surf iron men and male runners, on soft dry beach sand and grass. *European Journal of Applied Physiology* **86(1)**, 62-70. https://doi.org/10.1007/s004210100472

Pinnington, H.C., Lloyd, D.G., Besier, T.F. and Dawson, B. (2005) Kinematic and electromyography analysis of submaximal differences running on a firm surface compared with soft, dry sand. *European Journal of Applied Physiology* **94(3)**, 242-253. https://doi.org/10.1007/s00421-005-1323-6

Polczyk, M. and Zatoń, M. (2015) Effects of glycolytic-based interval training on anaerobic capacity in soccer players. *Human Movement* **16(3)**, 149-162. https://doi.org/10.1515/humo-2015-0041

Rampinini, E., Coutts, A.J., Castagna, C., Sassi, R. and Impellizzeri, F.M. (2007) Variation in top level soccer match performance. *International Journal of Sports Medicine* **28(12)**, 1018-1024. https://doi.org/10.1055/s-2007-965158

Ross, A. and Leveritt, M. (2001) Long-term metabolic and skeletal muscle adaptations to short-sprint training. *Sports Medicine* **31(15)**, 1063-1082. https://doi.org/10.2165/00007256-200131150-00003

Sanchez-Sanchez, J., Ramirez-Campillo, R., Petisco, C., Gonzalo-Skok, O., Rodriguez-Fernandez, A., Miñano, J. and Nakamura, F.Y. (2019) Effects of repeated sprints with changes of direction on youth soccer player's performance: Impact of initial fitness level. *The Journal of Strength and Conditioning Research* **33(10)**, 2753-2759. https://doi.org/10.1519/JSC.0000000000002232

Scarfone, R., Tessitore, A., Minganti, C., Capranica, L. and Ammendolia, A. (2015) Match analysis heart-rate and CMJ of beach soccer players during amateur competition. *International Journal of Performance Analysis in Sport* **15(1)**, 241-253. https://doi.org/10.1080/24748668.2015.11868790

Serpiello, F.R., McKenna, M.J., Bishop, D.J., Aughey, R.J., Caldow, M.K., Cameron-Smith, D. and Stepto, N.K. (2012) Repeated sprints alter signaling related to mitochondrial biogenesis in humans. *Medicine and Science in Sports and Exercise* **44(5)**, 827-834. https://doi.org/10.1249/MSS.0b013e318240067e

Shannon, E.S. and Carter, S.E. (2024) The effect of a 2-week ischaemic preconditioning intervention on anaerobic performance in male academy football players: a randomized, single-blinded, SHAM-controlled study. *Research in Sports Medicine* **32(6)**, 939-955. https://doi.org/10.1080/15438627.2023.2297192

Sindiani, M., Eliakim, A., Segev, D. and Meckel, Y. (2017) The effect of two different interval-training programmes on physiological and performance indices. *European Journal of Sport Science* **17(7)**, 830-837. https://doi.org/10.1080/17461391.2017.1321687

Singh, A., Sakshi, G. and Singh, S.J. (2014) Effect of plyometric training on sand versus grass on muscle soreness and selected sportspecific performance variables in hockey players. *Journal of Human Sport and Exercise* **9(1)**, 59-67. https://doi.org/10.4100/jhse.2014.91.07

Soares-Caldeira, L.F., de Souza, E.A., de Freitas, V.H., de Moraes, S.M., Leicht, A.S. and Nakamura, F.Y. (2014) Effects of additional repeated sprint training during preseason on performance, heart rate variability, and stress symptoms in futsal players: A randomized controlled trial. *The Journal of Strength and Conditioning Research* **28(10)**, 2815-2826. https://doi.org/10.1519/JSC.0000000000000461

Strydom, N.B., Bredell, G.A.G., Benade, A.J.S., Morrison, J.F., Viljoen, J.H. and Van Graan, C.H. (1966) The metabolic cost of marching at 3 mph over firm and sandy surfaces. *Internationale Zeitschrift für angewandte Physiologie einschließlich Arbeitsphysiologie* **23(2)**, 166-171. https://doi.org/10.1007/BF00699304

Taylor, J., Macpherson, T., Spears, I. and Weston, M. (2015) The effects of repeated-sprint training on field-based fitness measures: A meta-analysis of controlled and non-controlled trials. *Sports Medicine* **45(6)**, 881-891. https://doi.org/10.1007/s40279-015-0324-9

Thurlow, F., Huynh, M., Townshend, A., McLaren, S.J., James, L.P., Taylor, J.M., Weston, M. and Weakley, J. (2024) The effects of repeated-sprint training on physical fitness and physiological adaptation in athletes: A systematic review and meta-analysis. *Sports Medicine* **54(4)**, 953-974. https://doi.org/10.1007/s40279-023-01959-1

Thurlow, F., Weakley, J., Townshend, A.D., Timmins, R.G., Morrison, M. and McLaren, S.J. (2023) The acute demands of repeated-sprint training on physiological, neuromuscular, perceptual and performance outcomes in team sport athletes: A systematic review and meta-analysis. *Sports Medicine* **53(8)**, 1609-1640. https://doi.org/10.1007/s40279-023-01853-w

Vuong, J.L., Heil, J., Breuer, N., Theodoropoulos, M., Volk, N., Edel, A. and Ferrauti, A. (2023) Training on sand or parquet: Impact of pre-season training on jumping, sprinting, and change of direction performance in professional basketball players. *Applied Sciences* **13(14)**, 8518. https://doi.org/10.3390/app13148518

Weston, A.R., Myburgh, K.H., Lindsay, F.H., Dennis, S.C., Noakes, T.D. and Hawley, J.A. (1996) Skeletal muscle buffering capacity and endurance performance after high-intensity interval training by well-trained cyclists. *European Journal of Applied Physiology and Occupational Physiology* **75(1)**, 7-13. https://doi.org/10.1007/s004210050119

Zamparo, P., Perini, R., Orizio, C., Sacher, M. and Ferretti, G. (1992) The energy cost of walking or running on sand. *European Journal of Applied Physiology and Occupational Physiology* **65(2)**, 183-187. https://doi.org/10.1007/BF00705078

Zhang, J., Wei, A. and Xie, C. (2024) Effects of sprint interval training surface on physical fitness attributes of collegiate female soccer players: Identifying individual responses to training on grass, sand, and land surfaces. *Journal of Sports Science and Medicine* **23(2)**, 465-474. https://doi.org/10.52082/jssm.2024.465

Ziogas, G.G., Patras, K.N., Stergiou, N. and Georgoulis, A.D. (2011) Velocity at lactate threshold and running economy must also be considered along with maximal oxygen uptake when testing elite soccer players during preseason. *The Journal of Strength and Conditioning Research* **25(2)**, 414-419. https://doi.org/10.1519/JSC.0b013e3181bac3b9

Key points

- Six weeks of repeated-sprint training implemented within scheduled team sessions improved jump performance, repeated-sprint performance indices, and aerobic fitness compared with time-matched standard technical training.
- When session frequency and duration were time-matched and sprint structure was identical, sand-based RST elicited greater improvements than grass-based RST in jumping and selected indices of repeated-sprint fatigue resistance, including squat jump and RAST mean and minimum power and fatigue index.
- Aerobic adaptations were broadly similar between sand and grass, and no clear surface specific advantage was observed for running economy.

AUTHOR BIOGRAPHY

Hao YAN
Employment
College of Strength and Conditioning Training, Beijing Sport University, Beijing, China
Degree
PhD
Research interests
Sports training, soccer, etc.
E-mail: yhao0531@163.com

Haiting ZHAI
Employment
College of Sports Coaching, Beijing Sport University, Beijing, China
Degree
PhD
Research interests
Sports training, etc.
E-mail: minghuhaiting@163.com

Tingting WANG
Employment
College of Strength and Conditioning Training, Beijing Sport University, Beijing, China
Degree
MEd
Research interests
Sports training, soccer, etc.
E-mail: 2023210118@bsu.edu.cn

Duchun WANG
Employment
Chinese Table Tennis Association, Beijing, China.
Degree
MEd
Research interests
Sports medicine.
E-mail: 375345815@qq.com

Hongwen WEI
Employment
College of Strength and Conditioning Training, Beijing Sport University, Beijing, China
Degree
PhD
Research interests
Sports Sciences, soccer.
E-mail: weihw@bsu.edu.cn

✉ **Hongwen Wei**
College of Strength and Conditioning Training, Beijing Sport University, Beijing, China