

Indoor vs. beach men's volleyball athletes: a comparison of lower body strength and power attributes

Received: 13 May 2026

Accepted: 24 June 2026

Published online: 20 July 2026

Cite this article as: Jiang D., Guo Z., Ling X. *et al.* Indoor vs. beach men's volleyball athletes: a comparison of lower body strength and power attributes. *BMC Sports Sci Med Rehabil* (2026). <https://doi.org/10.1186/s13102-026-01835-1>

Dongting Jiang, Zhenxiang Guo, Xiaoyu Ling, Jiaqing Xu, Qiuyu Yu, Boyi Dai, Chris Bishop & Yongming Li

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

Indoor vs. Beach Men's Volleyball Athletes: A Comparison of Lower Body Strength and Power Attributes

Dongting Jiang^{1,2}; Zhenxiang Guo³; Xiaoyu Ling⁴; Jiaqing Xu⁵; Qiuyu Yu⁶; Boyi Dai⁷;

Chris Bishop⁵; Yongming Li^{1,2,8*}

1. School of Athletic Performance, Shanghai University of Sport, Shanghai, China
2. School of Coaching, Shanghai University of Sport, Shanghai, China
3. Sports coaching college, Beijing sport university, Beijing, China
4. School of Physical Education, Southwest University, Chongqing, China
5. Faculty of Science and Technology, London Sport Institute, Middlesex University, London, England, United Kingdom
6. Beijing Lucheng Sports Technology School, Beijing, China
7. Department of Rehabilitation and Movement Science, University of Vermont, Burlington, United States
8. China Institute of Sport Science, Beijing, China

* **Corresponding author:** Yongming Li

Email Address of the Corresponding Author: liyongming@sus.edu.cn

Abstract

Background: Indoor and beach volleyball are performed under contrasting surface and game constraints, but direct comparisons of lower-limb neuromuscular performance in highly trained players are limited. Therefore, this study compared the lower-limb neuromuscular profiles of highly trained male indoor and beach volleyball athletes.

Methods: In this cross-sectional study, 46 highly trained, national-level male volleyball athletes (indoor, $n = 26$; beach, $n = 20$) completed a standardised battery of lower-limb neuromuscular assessments in a single indoor session, including the isometric mid-thigh pull (IMTP), squat jump (SJ), countermovement jump (CMJ), drop jump (DJ), 10-30 m sprints, and the change-of-direction (COD) T-test. From the force and jump data, the rate of force development over the first 100 ms (RFD-100ms), reactive strength index (RSI), dynamic strength index (DSI), and eccentric utilisation ratio (EUR) were derived. Between-group differences were examined using independent-samples t-tests, with effect sizes reported as Hedges' g and 95% confidence intervals.

Results: Indoor players showed markedly faster COD performance, a higher RFD-100ms, and a higher RSI than beach players (T-test: 8.60 ± 0.31 vs 9.32 ± 0.47 s, $g = 1.83$, 95% CI 1.15 to 2.52, $p < 0.05$; RFD-100ms: 13421 ± 4660 vs 9883 ± 2536 N·s⁻¹, $g = 0.89$, 95% CI 0.29 to 1.50, $p < 0.05$; RSI: 2.08 ± 0.53 vs 1.75 ± 0.47 m·s⁻¹, $g = 0.63$, 95% CI 0.04 to 1.22, $p < 0.05$). No clear between-group differences were observed for IMTP peak force, jump height (SJ, CMJ, DJ), 30-m sprint time, DSI, or EUR (all $p > 0.05$). Beach players recorded slightly faster 10-m and 20-m sprint times, although these differences were not statistically significant (10 m: 1.83 ± 0.15 vs 1.78 ± 0.12 s, $g = 0.39$, 95% CI -0.18 to 0.97; 20 m: 3.12 ± 0.20 vs 3.04 ± 0.27 s, g

= 0.35, 95% CI -0.23 to 0.93).

Conclusion:

Highly trained male indoor and beach volleyball athletes exhibited discipline-specific lower-limb neuromuscular profiles. Indoor players were faster in COD, with higher RFD_{100ms} and RSI, consistent with a velocity- and reactivity-oriented profile, whereas beach players showed no such advantage, possibly reflecting the force and stability demands of sand. These differences may inform targeted lower-limb neuromuscular training for each format.

Keywords: Indoor volleyball; Beach volleyball; Lower-limb neuromuscular performance; Change of direction

Introduction

Volleyball, in both its indoor and beach formats, is a dynamic sport that demands high levels of physical conditioning, with lower-limb neuromuscular performance being a cornerstone of success (Cabarkapa et al., 2024a; Cabarkapa et al., 2024b). Key actions such as jumping, sprinting, and rapid changes of direction (COD) are fundamental to performance, influencing both offensive and defensive efficacy (Milić et al., 2025). Despite sharing a common origin, indoor and beach volleyball have evolved into distinct disciplines with unique environmental constraints and physiological demands that likely foster divergent physical adaptations in athletes.

The most profound difference between the two sports is the playing surface. Indoor volleyball is played on a hard, stable surface (e.g., hardwood or synthetic court), which provides a firm base for efficient force transfer, enabling rapid acceleration, high-velocity movements, and powerful vertical jumps (Dos'Santos et al., 2018). This environment places a premium on a well-developed stretch-shortening

cycle (SSC), enabling athletes to store and reutilise elastic energy effectively during explosive movements (Komi & Bosco, 1978). In contrast, beach volleyball is contested on sand, an unstable and energy-dissipating surface. Movement on sand requires greater muscular effort for stabilization and propulsion, typically leading to longer ground contact times and attenuated peak forces (Lesinski et al., 2016). This environment may dampen the efficacy of the SSC and place a greater emphasis on concentric muscular strength to overcome the surface's resistance.

Beyond the surface, game dynamics also differ substantially. The indoor game, with six players per side, involves highly specialized roles and tactical systems that necessitate short, maximal-intensity sprints and frequent, explosive jumps within a confined playing area. The pace is rapid, with minimal time between rallies, demanding high levels of anaerobic power and agility. By contrast, beach volleyball is contested in a two-player format, requiring athletes to be more all-round and to cover a substantially larger court area per player (Đurković et al., 2024). This results in more continuous, submaximal movements interspersed with maximal efforts, placing a greater demand on muscular endurance and stamina alongside explosive power (Rebelo et al., 2023).

Given these fundamental distinctions, it is plausible to hypothesize that long-term participation and training in these respective environments may lead to specific, chronic adaptations in the neuromuscular systems of elite athletes. Indoor players may develop a profile optimized for rapid force production (high rate of force development, RFD), reactive strength, and efficient COD mechanics. Beach volleyball athletes, while also requiring explosive power, are exposed to the higher energetic demands of sand-based locomotion and jumping, which can promote strength–endurance adaptations; however, the compliant sand surface is associated

with lower power and leg stiffness during reactive jump tasks, which may constrain maximal reactive performance, particularly in movements that rely on rapid stretch-shortening actions, compared with rigid court surfaces (Balasas et al., 2017). Neuromuscular training programs have been shown to improve performance and alter biomechanics in athletes (Myer et al., 2005; Filipa et al., 2010; Trajković & Bogataj, 2020), and the distinct training environments of indoor and beach volleyball can be seen as a form of long-term, sport-specific neuromuscular conditioning.

While numerous studies have examined the physical characteristics of volleyball players within a single discipline (Huston & Wojtys, 1996; Gonçalves et al., 2021; Abad et al., 2022), there is a notable lack of research providing a direct, comprehensive comparison of lower-limb neuromuscular profiles between elite-level indoor and beach players. Understanding these differences is crucial for optimizing training methodologies, refining talent identification processes, and facilitating athlete transitions between disciplines. Therefore, the purpose of this study was to conduct a comprehensive comparison of lower-limb neuromuscular performance, encompassing assessment of maximal strength, explosive power, speed, and change of direction performance on a hard surface across elite male indoor and beach volleyball players. We hypothesized that indoor players would exhibit superior performance on a hard surface in measures of neuromuscular and COD ability, reflecting adaptations to their fast-paced, hard-surface playing environment.

Methods

Participants

Forty-six male volleyball athletes participated in this study (indoor volleyball: $n = 26$; beach volleyball: $n = 20$). All were members of provincial volleyball teams

competing within the national competition system and were therefore classified as Tier 3 (highly trained / national level) in the performance-tier framework (McKay et al., 2022). The participants were 24.22 ± 3.45 years old, with a body mass of 89.81 ± 9.02 kg, a height of 197.44 ± 5.90 cm, and a training experience of 7.20 ± 1.44 years. The inclusion criteria were as follows: (1) continuous sport-specific training for at least five years, with a current training frequency of no less than five sessions per week (≥ 90 min each); (2) participation in official national competitions within the previous six months; (3) attainment of National First-Class Athlete qualification; (4) free of lower-limb injury for at least six months and no history of lower-limb surgery; and (5) willingness to complete all experimental tests and provide signed informed consent. Before the trials, athletes were informed of the procedures, including the possible risks involved, and signed an informed consent form. The study protocol received approval from the Ethics Committee of Beijing Sport University (2025220H).

Sample size estimation and justification

Due to the specific nature of elite sports settings, the sample size was determined by the available number of professional athletes within the collaborating organization, representing a convenience sample. As this study did not involve a priori power analysis, a sensitivity power analysis was conducted using G*Power (version 3.1.9.7) to determine the minimum detectable effect size (MDES), following the recommendations for exploratory/practical research by Ditroilo et al. (2025). With our sample size of $N = 46$ ($n_1 = 26$, $n_2 = 20$), an alpha of 0.05, and a power of 0.80, the study was sensitive enough to detect a large effect size of Hedges' $g = 0.83$.

Design

This cross-sectional study was designed to compare lower-limb neuromuscular performance characteristics between highly trained / national-level male indoor ($n = 26$) and beach ($n = 20$) volleyball athletes. All tests were completed in a single session per athlete during the competitive season, on the same indoor volleyball court and using identical testing procedures. Testing was conducted under standardized environmental conditions (average temperature of $22.1 \pm 1.3^{\circ}\text{C}$, range: 20 - 24°C ; average humidity of $60.5 \pm 6.2\%$, range: 55 - 70%).

All participants completed a battery of lower-limb neuromuscular tests, including squat jump (SJ, cm), countermovement jump (CMJ, cm), drop jump (DJ, cm), the T-test (s), 10-, 20-, and 30-m sprint times (s), and the isometric mid-thigh pull (IMTP, N). Tests were administered in a fixed order: (1) jump tests (SJ, CMJ, DJ), (2) change-of-direction test (T-test), (3) linear sprint tests (10-, 20-, and 30-m), and (4) maximal strength test (IMTP). Participants completed a standardised 15-min warm-up consisting of light jogging, dynamic stretching, progressive accelerations, and submaximal jumps, followed by 2 - 3 min of passive recovery before commencing the first test. Passive rest of 5 - 7 min was provided between test categories, and 2 - 3 min was allowed between repeated trials within the same test. All procedures were supervised by the same group of investigators. Standardised verbal instructions were provided before each trial, and participants were instructed to perform each effort maximally.

Insert Figure 1 here.

Figure 1. Overview of the study design and testing session procedures.

Measurements

Isometric Mid-Thigh Pull (IMTP)

Maximal isometric strength was assessed using a custom-built IMTP rig with dual force plates (ForceDecks; VALD Performance, Brisbane, Australia) sampling at 1000 Hz. The force plates were positioned under the participant's feet, and participants stood shoulder-width apart with one foot on each plate, adopting a posture consistent with the second pull of a clean, with the internal knee angle set to approximately $125 \sim 135^\circ$ and the internal hip angle set to $140 \sim 150^\circ$ (Joffe et al., 2025). An immovable barbell was adjusted individually and fixed at mid-thigh height. On command, participants were instructed to pull upward as rapidly and forcefully as possible for 5 s (Nuzzo et al., 2008). Three maximal trials were performed, and the best trial was retained for analysis. **Peak force was defined as the maximum total vertical force recorded during the 5-s effort and was retained as the index of maximal isometric strength.** Rapid force production was quantified as $\text{RFD}_{-100\text{ms}}$ ($\text{N}\cdot\text{s}^{-1}$), calculated as the mean rate of force development over the first 100 ms from contraction onset using the total vertical force summed across both force plates (Smith et al., 2024).

Squat Jump (SJ)

Squat jump performance was assessed using dual force plates (ForceDecks; VALD Performance, Brisbane, Australia) sampling at 1000 Hz. Participants stood with feet shoulder-width apart, placing one foot on each force plate, and kept their hands on the hips. They adopted a static semi-squat position with the knee angle set at approximately 90° and maintained this position for 2 s before performing a maximal vertical jump without any countermovement (Latocha, 2025). Three maximal trials were performed, and the trial yielding the greatest jump height was retained to represent maximal SJ performance. To ensure a true SJ, each trial was manually

inspected by reviewing the force-time trace alongside visual observation to confirm a stable pre-jump hold and the absence of any small-amplitude countermovement; non-compliant trials were discarded and repeated. Jump height was calculated using the impulse-momentum method from the summed vertical ground reaction force-time data (Harry et al., 2018).

Countermovement Jump (CMJ)

Countermovement jump performance was assessed using dual force plates (ForceDecks; VALD Performance, Brisbane, Australia) sampling at 1000 Hz. Participants stood with feet shoulder-width apart, placing one foot on each force plate, and kept their hands on the hips. From an upright standing position, participants performed a rapid countermovement to a self-selected depth and immediately executed a maximal vertical jump (Buchheit et al., 2010). Three maximal trials were performed, and the trial yielding the greatest jump height was retained for analysis. Jump height was calculated using the impulse-momentum method from the summed vertical ground reaction force-time data (Harry et al., 2018). **In addition, CMJ peak force (the maximum total vertical force during the propulsion phase) was extracted for use in the derived indices described below.**

Drop Jump (DJ)

Drop jump performance was assessed using dual force plates (ForceDecks; VALD Performance, Brisbane, Australia) sampling at 1000 Hz. **Participants stood on a box positioned immediately adjacent to the force plates, using a fixed drop height of 40 cm. This height did not exceed the group mean CMJ height obtained during preliminary testing, ensuring that the eccentric landing demands remained tolerable**

across participants. On a standardized cue, participants stepped off the box and landed with both feet simultaneously on the force plates, then immediately performed a rebound jump while aiming to maximize jump height and minimize ground contact time. Hands were kept on the hips throughout. Three maximal trials were performed, and the trial yielding the greatest jump height was retained for analysis. Jump height was calculated from flight time derived from the summed vertical ground reaction force–time signal, and the reactive strength index (RSI, $\text{m}\cdot\text{s}^{-1}$) was calculated as jump height divided by ground contact time (Xu et al., 2024).

Sprint Tests

Linear sprint performance over 10, 20, and 30 m was assessed using an electronic timing gate system (SmartSpeed; Fusion Sport, Brisbane, Australia). Timing gates were positioned at 0, 10, 20, and 30 m, with the beams set at approximately hip height to minimise inadvertent triggering by limb movement. Participants used a stationary two-point standing start with a staggered stance, were free to select their lead leg, and kept the same lead leg across trials (Nimphius et al., 2016). A start line was marked 0.30 m behind the first timing gate, and participants positioned the lead foot at the start line before initiating the sprint on the start signal without any pre-movement, sprinting through all timing gates (Nimphius et al., 2016). Trials were discarded and repeated if any discernible rocking or pre-movement occurred prior to the start. Three maximal trials were completed, and the fastest trial was retained for analysis; 10-, 20-, and 30-m split times were extracted from this trial. Sprint times were recorded to the nearest 0.01 s (Furlong et al., 2021).

Change of Direction Test (T-test)

Change-of-direction (COD) speed was assessed using a standard T-test protocol (Pereira et al., 2018). The test was selected because it incorporates short-distance forward sprinting, lateral shuffling, and backward running, reflecting the multidirectional movement demands of volleyball (Pauole et al., 2000; Lockie et al., 2020; Oliveira et al., 2025). Four cones were arranged in a T configuration, with cone A at the start/finish line, cone B positioned 10 m directly ahead of cone A, and cones C and D positioned 5 m to the left and right of cone B, respectively. Time was recorded using the same dual-beam electronic timing system (SmartSpeed; Fusion Sport, Brisbane, Australia), with timing gates aligned at the start/finish line and the beams set at approximately hip height. A start line was marked 0.30 m behind the timing gates. Participants started from a stationary two-point standing start with a staggered stance, facing forward, with the lead foot positioned at the marked start line 0.30 m behind the timing gates; the selected lead leg was kept consistent across trials, and participants initiated the test on the verbal start signal without any pre-movement (Nimphius et al., 2016). Participants sprinted to cone B, shuffled laterally to cone C, shuffled across to cone D, shuffled back to cone B, and then ran backward to cone A to complete the trial. Lateral movements were performed as shuffles without crossing the feet. Trials were discarded and repeated if any discernible rocking or pre-movement occurred prior to the start. Three maximal trials were performed, and the fastest time was retained for analysis. T-test time was recorded to the nearest 0.01 s (Nimphius et al., 2016).

Derived Indices

Two derived indices were computed from the primary force-plate outcomes. The dynamic strength index (DSI, AU) was calculated as the ratio of CMJ peak force to

IMTP peak force, reflecting an athlete's ability to express maximal isometric strength under ballistic conditions (Sheppard et al., 2011). The eccentric utilization ratio (EUR, AU) was calculated as the ratio of CMJ height to SJ height, reflecting the extent to which an athlete utilizes the countermovement (eccentric pre-stretch) to augment jump performance, thereby serving as an index of SSC utilization (McGuigan et al., 2006).

Statistical Analysis

Descriptive data are presented as means $\pm$ standard deviation (SD). The normality of each variable and the homogeneity of variance between groups were assessed using the Shapiro-Wilk test and Levene's test, respectively. When variables were clearly non-normally distributed, data were log-transformed prior to analysis; for clarity and practical interpretation, results are reported as back-transformed values where applicable.

Test-retest reliability was evaluated for all performance measures, with relative reliability quantified using the intraclass correlation coefficient (ICC) with 95% confidence intervals (CI), and absolute reliability quantified using the coefficient of variation (CV) with 95% CI.

Between-group differences (IVP vs. BVP) were examined using independent-samples t-tests. Standardized between-group differences were expressed as Hedges' g with 95% CI (Lakens, 2013). The magnitude of effect sizes was interpreted using the absolute value of g ($|g|$) as trivial (< 0.20), small ($0.20-0.59$), moderate ($0.60-1.19$), large ($1.20-1.99$), and very large (≥ 2.0) (Hopkins et al., 2009). Statistical significance was set at $p < 0.05$. All analyses were performed in R (version 4.3.0; R Foundation for Statistical Computing, Vienna, Austria) using the tidyverse collection for data

processing and ggplot2 for data visualization.

Results

Table 1 summarises the anthropometric and neuromuscular performance characteristics of indoor (IVP) and beach (BVP) volleyball players, together with test–retest reliability (ICC and CV, both with 95% CI). The two groups were comparable in age, height, body mass, and training experience.

The largest between-group difference was in COD performance, where IVP completed the T-test ~8% faster than BVP ($g = 1.83$, $p < 0.05$). The same pattern held for the rapid- and reactive-force indices, with IVP showing higher RFD_{-100ms} (~36%; $g = 0.89$, $p < 0.05$) and a higher RSI (~19%; $g = 0.63$, $p < 0.05$), together indicating a faster, more reactive force profile in indoor players. No other outcome differed significantly. Maximal isometric strength, jump height in the SJ, CMJ, and DJ, and 30-m sprint time were comparable between the groups, BVP were only nominally faster over 10–20 m (~2–3%), and the derived ratios DSI and EUR did not differ. Across these outcomes the effects were trivial to small ($|g| \leq 0.52$) and the 95% confidence intervals all included zero. Full descriptive data and effect sizes are presented in Table 1 and Figure 2.

Insert Table 1 here.

Table 1. Descriptive statistics and test-retest reliability (ICC and CV, both with 95% CI) for anthropometric and performance measures in indoor and beach volleyball players.

Insert Table 2 here.

Table 2. Between-group differences (Hedges' g with 95% CI) in strength, jump, sprint, change-of-direction outcomes, and derived indices in indoor and beach volleyball players.

Insert Figure 2 here.

Figure 2. Between-group differences (Hedges' g with 95% CI) in strength, jump, sprint, change-of-direction outcomes, and derived indices in indoor and beach volleyball players.

Abbreviations: IVP, indoor volleyball players; BVP, beach volleyball players; IMTP, isometric mid-thigh pull; SJ, squat jump; DJ, drop jump; CMJ, countermovement jump; T-test, T-test change-of-direction test; RFD_{-100ms} , rate of force development over the first 100 ms; DSI, dynamic strength index; RSI, reactive strength index; EUR, eccentric utilization ratio; ES, effect size (Hedges' g); AU, arbitrary units.

Notes: *: $p < 0.05$; **: $p < 0.01$; ***: $p < 0.001$. ES is reported as Hedges' g [95% CI].

Discussion

This study provides a comprehensive comparison of lower-limb neuromuscular performance between male indoor and beach volleyball players. Overall, the findings provide support for our primary hypothesis by suggesting discipline-specific performance profiles, with indoor players demonstrating better COD performance and more favourable indices of rapid force production and reactive strength. These contrasts may reflect chronic adaptations to discipline-specific movement demands performed under different surface conditions, with sand imposing different mechanical constraints than a rigid indoor court.

COD may represent a key performance characteristic distinguishing indoor from beach volleyball players, potentially reflecting the frequent acceleration-deceleration and multi-directional movement demands inherent to the indoor game (Đurković et al., 2024). By comparison, linear sprint tests over 10 - 30 m may be less sensitive to discipline-specific differences because volleyball match play rarely involves sustained straight-line running; instead, athletes repeatedly accelerate, brake, and re-accelerate over short, multi-directional distances (Đurković et al., 2024). These findings are logically consistent with the demands of indoor volleyball, which is characterized by explosive, multi-directional movements over short distances on a hard, responsive court (Hank et al., 2024). The rigid, high-friction court surface allows for efficient transmission of ground reaction forces, enabling rapid acceleration, deceleration, and changes in direction essential for defensive and offensive (Dos'Santos et al., 2018). Conversely, beach volleyball is performed on sand, a compliant and energy-dissipating surface. Prior studies have reported that running and sprinting on sand increases the energetic cost and alters movement mechanics compared with firm ground, which may constrain rapid acceleration and sharp COD (Zamparo et al., 1992; Lejeune et al., 1998; Pinnington & Dawson, 2001; Gaudino et al., 2013; Hank et al., 2024). Rather than simply reducing “speed”, the sand environment may encourage different force-application strategies, with athletes needing to apply force over a longer ground-contact period to accumulate sufficient horizontal impulse for propulsion (Gaudino et al., 2013; Lesinski et al., 2016). Notably, this impulse-oriented strategy mirrors the technical demands of early sprint acceleration and may enable compensatory acceleration strategies, thereby attenuating between-discipline differences in short-sprint performance. Overall, long-term exposure to indoor volleyball may be more closely associated with enhanced COD capacity, whereas

linear sprint performance appears to show less consistent separation between disciplines.

To further interpret these discipline-related differences, rapid force production was considered as a potential contributor. Indoor players showed higher RFD_{-100ms} , a commonly used marker of explosive force production (Newton et al., 1999), although this finding should be interpreted cautiously given the known variability of RFD and the relatively higher CV observed in the present study. Mechanistically, rapid force production may support shorter ground-contact times during sprinting and jumping, and a rigid, high-friction court may facilitate the translation of this capacity into braking and re-acceleration performance (Figueira et al., 2025). In contrast, sand is demonstrably more compliant and energy-dissipating, which may favour movement solutions that rely more on sustained force application than maximal rates of force rise (Schleitzer et al., 2022).

Furthermore, indoor players exhibited higher RSI, suggesting more effective reactive strength characteristics during fast SSC actions. RSI reflects the ability to rapidly transition from an eccentric to a concentric muscle action, utilizing stored elastic energy to augment power output (Sheppard et al., 2008). This is paramount in indoor volleyball, where players perform numerous consecutive jumps for blocking and attacking. The stiff, non-compliant indoor surface facilitates an efficient SSC. In contrast, the deformable sand surface in beach volleyball absorbs impact forces, prolonging ground contact time and dampening the elastic energy return, thereby making a highly reactive SSC less effective (Lesinski et al., 2016). This environmental constraint likely leads beach players to rely more on concentric muscle strength for jumping, as opposed to the reactive, elastic-driven jumping strategy. This aligns with biomechanical principles suggesting that greater leg stiffness is

advantageous for performance on firm surfaces (Moore, 2016), a quality intrinsically linked to a high RSI. This leads to a “force-dominant” strategy in beach players, as opposed to the “velocity-dominant” or “reactive” strategy of indoor players.

One of the more informative observations was the lack of clear between-group differences in maximal isometric strength (IMTP peak force) and vertical jump height (SJ and CMJ), with small effects and confidence intervals overlapping zero. This pattern suggests that highly trained, national-level athletes in both disciplines may develop broadly comparable maximal lower-limb strength and a similar capacity to express it during non-reactive or longer-duration SSC jump tasks. Beach volleyball players likely accumulate substantial high-force exposure through repeated locomotion and jumping on sand, which may provide a chronic resistance-like stimulus (Nunes et al., 2021), whereas indoor players may develop strength through structured resistance training and the high-impact nature of the sport (Newton et al., 2006). A more plausible differentiator may therefore lie not in maximal strength itself, but in how rapidly force can be expressed and how effectively it is utilised during fast, reactive tasks, consistent with the principle of training specificity (Loturco et al. 2015). Neither DSI nor EUR differed clearly between groups, with small effects and confidence intervals including zero. The higher RSI but similar EUR may reflect that the two indices capture different aspects of SSC function, RSI a reactive, short-contact rebound with a high-velocity, imposed pre-stretch and EUR the augmentation from a slower, self-initiated countermovement (McGuigan et al., 2006; Flanagan et al., 2008). Indoor players’ habitual fast, short-contact jumping on a rigid court may develop the reactive capacity RSI reflects, whereas sand training, by prolonging contact and dampening elastic return, may provide a weaker stimulus and could help explain beach players’ lower RSI even on firm ground. By contrast, the slower

countermovement underlying EUR appears less sensitive to such differences. As the design is cross-sectional and contact times were unmeasured, this interpretation is tentative and best read as associative rather than causal.

These findings have practical implications for training. Because indoor players were distinguished by faster COD and higher rapid- and reactive-force indices rather than greater maximal strength, programmes targeting indoor performance may prioritise reactive-strength and fast SSC work (e.g., drop jumps, short-contact hops) together with deceleration and re-acceleration drills. For beach players, whose jumping relies more on concentric force because the compliant sand dampens the SSC, training may instead emphasise concentric strength and power, alongside lower-limb stability and eccentric landing control to manage the unstable surface. Given the cross-sectional design, these recommendations remain practical suggestions rather than prescriptions.

This study has several limitations. First, given its cross-sectional design, this study identifies discipline-related associations rather than causal relationships, which longitudinal work could later confirm. Second, the relatively small convenience sample limited statistical power, so smaller between-group effects may have gone undetected. Third, several outcomes were derived or ratio-based (RFD-100ms, RSI, DSI, EUR) and are sensitive to data-processing choices; RFD-100ms in particular showed relatively high within-subject variability, so its interpretation warrants caution. Fourth, the metrics used did not allow a phase-specific analysis of force-time strategies (e.g., the duration of force application, contact-time components, or eccentric-concentric contributions to jumping); future work should add such metrics. Finally, all tests were performed on a single hard indoor surface, which may have favoured indoor players and did not reproduce beach-specific conditions (sand

instability, wind, temperature, and the greater energetic demands of locomotion on sand); testing both groups on rigid courts and sand would help establish whether the observed indoor advantage reflects genuine long-term adaptation or greater familiarity with the test surface.

Conclusions

This study compared lower-limb neuromuscular characteristics in highly trained, national-level male indoor and beach volleyball athletes and identified discipline-specific profiles. Maximal isometric strength (IMTP peak force) and jump height in the SJ and CMJ showed no clear between-group differences. In contrast, indoor players demonstrated markedly faster COD times and higher derived indices of rapid force and reactive strength (RFD_{-100ms} and RSI), whereas linear sprint performance showed only small, unclear between-group differences. Collectively, these findings suggest that indoor volleyball may place greater emphasis on rapid braking-reacceleration and reactive, short-contact SSC actions on a rigid court, while beach volleyball may encourage movement solutions that prioritise force applied over longer durations under the mechanical constraints of the unstable sand surface.

Authors' contributions

Dongting Jiang: research concept and study design, data collection, data analysis and interpretation, writing of the manuscript; Zhenxiang Guo: reviewing a draft of the manuscript; Xiaoyu Ling: reviewing a draft of the manuscript; Jiaqing Xu: reviewing a draft of the manuscript; Qiuyu Yu: data collection; Boyi Dai: reviewing a draft of the manuscript; Chris Bishop: reviewing a draft of the manuscript; Yongming Li: research concept and study design, reviewing a draft of the manuscript, editing a draft of the manuscript.

Funding

No sources of funding were used to assist in this article.

Data availability

All data generated or analyzed during this study are included in this published article.

Declarations**Ethics approval and consent to participate**

All participants provided written informed consent prior to participation.

Ethical statement

The study protocol received approval from the Ethics Committee of Beijing Sport University (2025220H) and was conducted in accordance with the Declaration of Helsinki.

Clinical trial number

not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

ARTICLE IN PRESS

References

- Abad, CCC, Lopes, MWR, Lara, JPR, et al. Long-term changes in vertical jump, H:Q ratio and interlimb asymmetries in young female volleyball athletes. *Int J Environ Res Public Health* 19: 16420, 2022.
- Balasas, DG, Christoulas, K, Stefanidis, P, et al. The effect of beach volleyball training on muscle performance of indoor volleyball players. *J Sports Med Phys Fitness* 58: 1240–1246, 2017.
- Buchheit, M, Spencer, M, and Ahmaidi, S. Reliability, usefulness, and validity of a repeated sprint and jump ability test. *Int J Sports Physiol Perform* 5: 3–17, 2010.
- Cabarkapa, DV, Cabarkapa, D, and Fry, AC. Starters vs non-starters differences in vertical jump force-time metrics in female professional volleyball players. *Front Sports Act Living* 6: 1389001, 2024a.
- Cabarkapa, DV, Cabarkapa, D, Philipp, NM, and Fry, AC. Competitive season-long changes in countermovement vertical jump force-time metrics in female volleyball players. *J Strength Cond Res* 38: e72–e77, 2024b.
- Dos'Santos, T, Thomas, C, Comfort, P, and Jones, PA. The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sports Med* 48: 2235–2253, 2018.
- Đurković, T, Babok, D, and Rešetar, T. Differences in game dynamics between high-level volleyball and beach volleyball matches. *J Funct Morphol Kinesiol* 9: 28, 2024.
- Figueira, B, Vincelovič, A, Batalha, N, and Paulauskas, R. Comparative analysis of external and internal loads in preparation male volleyball and beach volleyball matches. *BMC Sports Sci Med Rehabil* 17: 293, 2025.
- Filipa, A, Byrnes, R, Paterno, MV, Myer, GD, and Hewett, TE. Neuromuscular

training improves performance on the star excursion balance test in young female athletes. *J Orthop Sports Phys Ther* 40: 551–558, 2010.

Flanagan EP, Comyns TM. The use of contact time and the reactive strength index to optimize fast stretch-shortening cycle training. *Strength Cond J*. 2008;30:32-38.

Furlong, LAM, Harrison, AJ, and Jensen, RL. Measures of strength and jump performance can predict 30-m sprint time in rugby union players. *J Strength Cond Res* 35: 2579–2583, 2021.

Gaudino, P, Gaudino, C, Alberti, G, et al. Biomechanics and predicted energetics of sprinting on sand: Hints for soccer training. *J Sci Med Sport* 16: 271–275, 2013.

Gonçalves, CA, Lopes, TJD, Nunes, C, Marinho, DA, and Neiva, HP. Neuromuscular jumping performance and upper-body horizontal power of volleyball players. *J Strength Cond Res* 35: 2236–2241, 2021.

Hank, M, Cabell, L, Zahalka, F, et al. Differences in external load among indoor and beach volleyball players during elite matches. *PeerJ* 12: e16736, 2024.

Harry, JR, Barker, LA, James, R, and Dufek, JS. Performance differences among skilled soccer players of different playing positions during vertical jumping and landing. *J Strength Cond Res* 32: 304–312, 2018.

Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41:3-13.

Huston, LJ, and Wojtys, EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med* 24: 427–436, 1996.

Joffe, SA, Chavda, S, Gilham, J, Sandercock, GRH, and Tallent, J. A comparison of maximal isometric force in the first pull, transition and second pull of the clean and their contribution to predict performance in national and international level

weightlifters. *Sports Biomech* 1–17, 2025.

Komi, PV, and Bosco, C. Utilization of stored elastic energy in leg extensor muscles by men and women. *Med Sci Sports* 10: 261–265, 1978.

Lakens D. Calculating and reporting effect sizes to facilitate cumulative science: a practical primer for t-tests and ANOVAs. *Front Psychol.* 2013;4:863.

Latocha, A. Acute effects of isometric conditioning activity with different rest intervals between sets on countermovement jump performance in resistance-trained participants. *Appl Sci* 15: 11989, 2025.

Lejeune, TM, Willems, PA, and Heglund, NC. Mechanics and energetics of human locomotion on sand. *J Exp Biol* 201: 2071–2080, 1998.

Lesinski, M, Prieske, O, Demps, M, and Granacher, U. Effects of fatigue and surface instability on neuromuscular performance during jumping. *Scand J Med Sci Sports* 26: 1140–1150, 2016.

Lockie, RG, Dawes, JJ, and Callaghan, SJ. Lower-body power, linear speed, and change-of-direction speed in Division I collegiate women's volleyball players. *Biol Sport* 37: 423–428, 2020.

Loturco, I, Gil, S, de Souza Laurino, CF, et al. Differences in muscle mechanical properties between elite power and endurance athletes: A comparative study. *J Strength Cond Res* 29: 1723–1728, 2015.

McGuigan MR, Doyle TLA, Newton M, Edwards DJ, Nimphius S, Newton RU. Eccentric utilization ratio: effect of sport and phase of training. *J Strength Cond Res.* 2006;20:992-995.

McKay, AKA, Stellingwerff, T, Smith, ES, et al. Defining training and performance caliber: A participant classification framework. *Int J Sports Physiol Perform* 17: 317–331, 2022.

Milić, V, Radenković, O, Čaprić, I, et al. Sports injuries in basketball, handball, and volleyball players: Systematic review. *Life* 15: 529, 2025.

Moore, IS. Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Med* 46: 793–807, 2016.

Myer, GD, Ford, KR, Palumbo, JP, and Hewett, TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res* 19: 51–60, 2005.

Newton, RU, Kraemer, WJ, and Häkkinen, K. Effects of ballistic training on preseason preparation of elite volleyball players. *Med Sci Sports Exerc* 31: 323–330, 1999.

Newton, RU, Rogers, RA, Volek, JS, Häkkinen, K, and Kraemer, WJ. Four weeks of optimal load ballistic resistance training at the end of season attenuates declining jump performance of women volleyball players. *J Strength Cond Res* 20: 955–961, 2006.

Nimphius, S, Callaghan, SJ, Spiteri, T, et al. Change of direction deficit: A more isolated measure of change of direction performance than total 505 time. *J Strength Cond Res* 30: 3024–3032, 2016.

Nunes, A, Cattuzzo, MT, Faigenbaum, AD, and Mortatti, AL. Effects of integrative neuromuscular training and detraining on countermovement jump performance in youth volleyball players. *J Strength Cond Res* 35: 2242–2247, 2021.

Nuzzo, JL, McBride, JM, Cormie, P, and McCaulley, GO. Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. *J Strength Cond Res* 22: 699–707, 2008.

Oliveira, JP, Marinho, DA, Jacinto, P, et al. Characterization of physical performance and change of direction deficit across age groups in young female

volleyball players. *BMC Sports Sci Med Rehabil* 17: 209, 2025.

Pauole, K, Madole, K, Garhammer, J, Lacourse, M, and Rozenek, R. Reliability and validity of the T-test as a measure of agility, leg power, and leg speed in college-aged men and women. *J Strength Cond Res* 14: 443–450, 2000.

Pereira, LA, Nimphius, S, Kobal, R, et al. Relationship between change of direction, speed, and power in male and female national Olympic team handball athletes. *J Strength Cond Res* 32: 2987–2994, 2018.

Pinnington, HC, and Dawson, B. The energy cost of running on grass compared to soft dry beach sand. *J Sci Med Sport* 4: 416–430, 2001.

Rebelo, A, Pereira, JR, Martinho, DV, et al. Training load, neuromuscular fatigue, and well-being of elite male volleyball athletes during an in-season mesocycle. *Int J Sports Physiol Perform* 18: 354–362, 2023.

Schleitzer, S, Wirtz, S, Julian, R, and Eils, E. Development and evaluation of an inertial measurement unit (IMU) system for jump detection and jump height estimation in beach volleyball. *Ger J Exerc Sport Res* 52: 228–236, 2022.

Sheppard JM, Chapman D, Taylor KL. An evaluation of a strength qualities assessment method for the lower body. *J Aust Strength Cond.* 2011;19:4-10.

Sheppard, JM, Cronin, JB, Gabbett, TJ, et al. Relative importance of strength, power, and anthropometric measures to jump performance of elite volleyball players. *J Strength Cond Res* 22: 758–765, 2008.

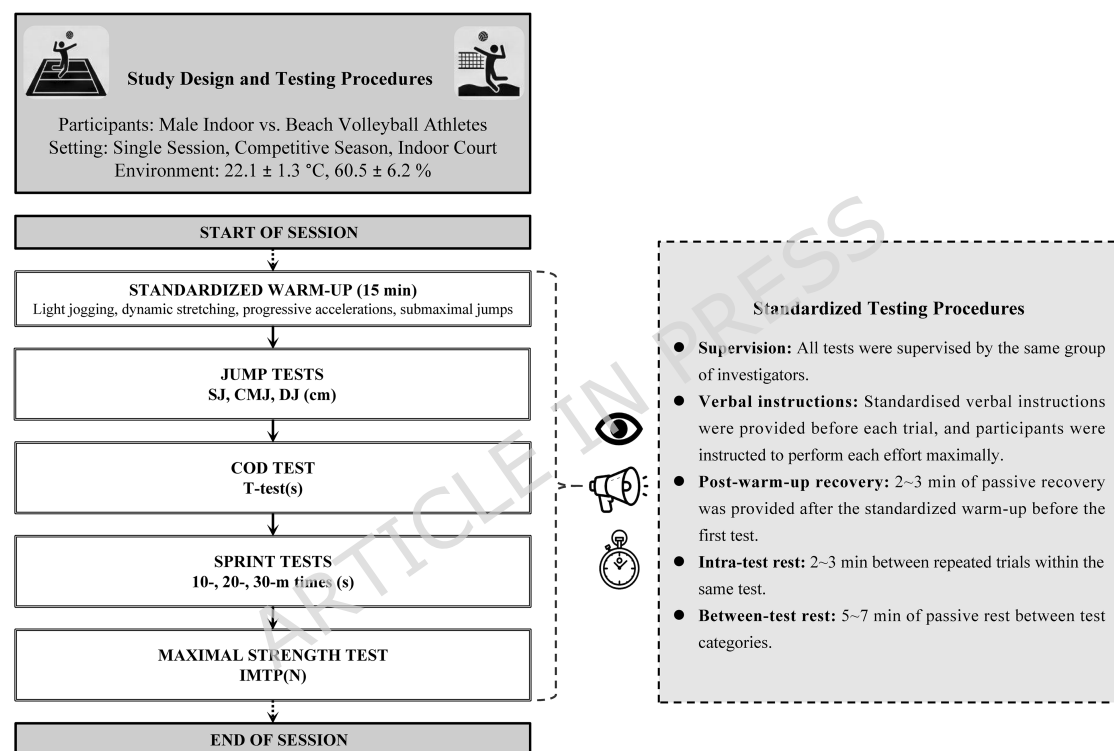
Smith, ES, Weakley, J, McKay, AKA, et al. Minimal influence of the menstrual cycle or hormonal contraceptives on performance in female rugby league athletes. *Eur J Sport Sci* 24: 1067–1078, 2024.

Trajković, N, and Bogataj, Š. Effects of neuromuscular training on motor competence and physical performance in young female volleyball players. *Int J*

Environ Res Public Health 17: 1755, 2020.

Xu, J, Turner, A, Comyns, TM, Chavda, S, and Bishop, C. The countermovement rebound jump: Between-session reliability and a comparison with the countermovement and drop jump tests. J Strength Cond Res 38: e150–e159, 2024.

Zamparo, P, Perini, R, Orizio, C, et al. The energy cost of walking or running on sand. Eur J Appl Physiol Occup Physiol 65: 183–187, 1992.



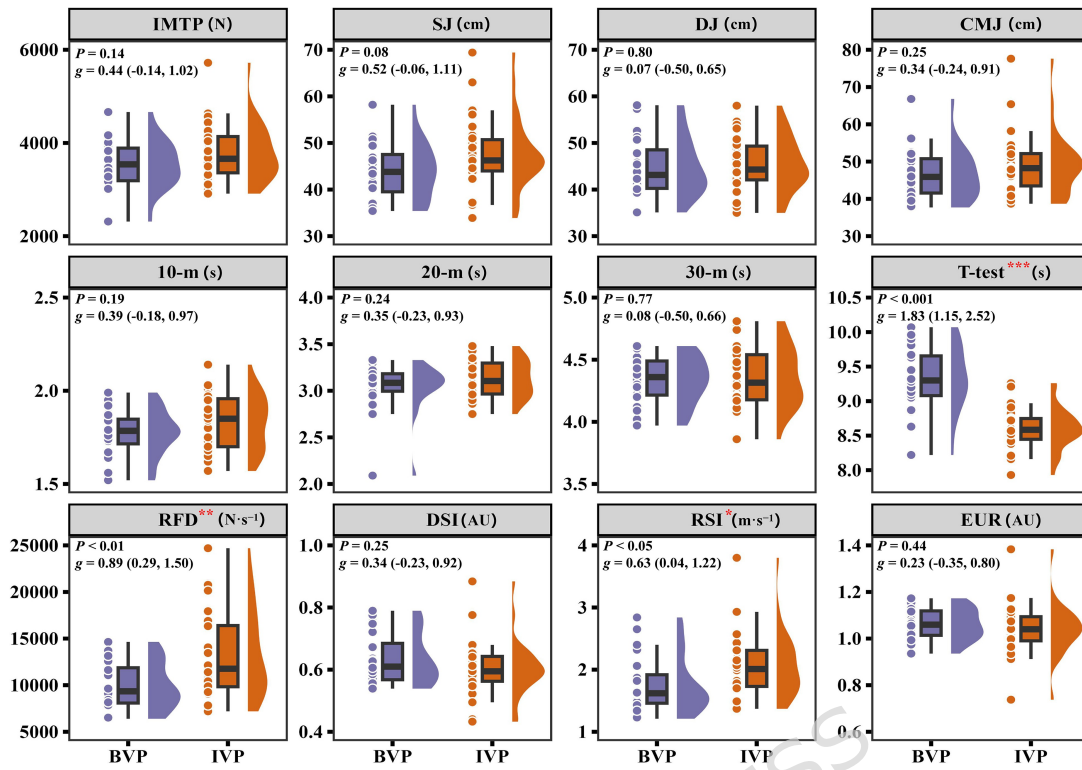


Table 1. Descriptive statistics and test-retest reliability (ICC and CV, both with 95% CI) for anthropometric and performance measures in indoor and beach volleyball players.

Test	Metrics Name	IVP (<i>n</i> = 26)	ICC (95% CI)	CV (95% CI)	BVP (<i>n</i> = 20)	ICC (95% CI)	CV (95% CI)
Anthropometric characteristics	Age (years)	24.54 ± 3.70	-	-	23.80 ± 3.14	-	-
	Height (m)	197.00 ± 7.19	-	-	198.02 ± 3.69	-	-
	Body mass (kg)	90.36 ± 8.23	-	-	89.09 ± 10.14	-	-
	Training experience (years)	7.35 ± 1.41	-	-	7.00 ± 1.49	-	-
	Maximal Strength	IMTP (N)	0.90	5.45	3541.85	0.89	3.66
			(0.79, 0.95)	(3.87, 7.03)	± 523.94	(0.74, 0.95)	(2.12, 5.20)
Performance	RFD _{-100ms} (N·s ⁻¹)	13421.46 ± 4659.86	0.88	(13.59, 23.82)	9882.55 ± 2535.92	(0.66, 0.93)	13.51 (11.49, 15.52)
			0.88	4.40		0.86	5.21
Jump Performance	SJ (cm)	47.70 ± 7.70	(0.76, 0.94)	(3.33, 5.48)	43.95 ± 6.11	(0.69, 0.94)	(3.47, 6.95)
			0.87	4.65		0.79	5.68
	DJ (cm)	45.50 ± 5.79	(0.74, 0.94)	(3.33, 5.98)	45.04 ± 6.33	(0.55, 0.91)	(4.59, 6.78)
			0.92	3.02		0.93	3.62
	CMJ (cm)	49.33 ± 8.49	(0.84, 0.96)	(2.14, 3.90)	46.61 ± 7.10	(0.83, 0.97)	(2.60, 4.65)
			0.90	6.52		0.82	9.76
Sprint Performance	RSI (m·s ⁻¹)	2.08 ± 0.53	(0.80, 0.95)	(5.55, 7.50)	1.75 ± 0.47	(0.61, 0.92)	(6.42, 13.10)
			0.71	5.62		0.63	6.60
	DSI (AU)	0.60 ± 0.09	(0.46, 0.85)	(4.13, 7.11)	0.63 ± 0.08	(0.28, 0.83)	(4.73, 8.47)
			0.56	4.82		0.54	7.43
	EUR (AU)	1.04 ± 0.11	(0.24, 0.77)	(3.81, 5.83)	1.06 ± 0.07	(0.15, 0.79)	(5.39, 9.47)
			0.71	4.04		0.68	4.53
		0.15	(0.46, 0.71)	(3.09, 4.04)	0.12	(0.46, 0.71)	(3.54, 5.47)

				0.85)	5.00)		84)	52)
				0.76	3.14		0.73	2.70
	20m (s)	3.12 ±		(0.54 ,	(2.86 ,	3.04 ±	(0.53 , 0.	(2.29 , 3.
ance		0.20		0.88)	3.42)	0.27	87)	11)
				0.85	1.45		0.78	2.10
	30m (s)	4.36 ±		(0.71 ,	(1.33 ,	4.34 ±	(0.61 , 0.	(1.66 , 2.
		0.24		0.93)	1.56)	0.19	90)	55)
COD				0.77	1.88		0.78	2.36
Perform	T-test (s)	8.60 ±		(0.56 ,	(1.80 ,	9.32 ±	(0.61 , 0.	(2.25 , 2.
ance		0.31		0.89)	1.96)	0.47	90)	47)

Abbreviations: IVP, indoor volleyball players; BVP, beach volleyball players; IMTP, isometric mid-thigh pull; SJ, squat jump; DJ, drop jump; CMJ, countermovement jump; COD, change of direction; T-test, T-test change-of-direction test; RFD_{-100ms}, rate of force development over the first 100 ms; DSI, dynamic strength index; RSI, reactive strength index; EUR, eccentric utilization ratio; ICC, intraclass correlation coefficient; CV, coefficient of variation; AU, arbitrary units.

Notes: ICC and CV are reported with 95% CI; “-” indicates not applicable/not assessed

Table 2. Between-group differences (Hedges' g with 95% CI) in strength, jump, sprint, change-of-direction outcomes, and derived indices in indoor and beach volleyball players.

Test	IVP (n = 26)	BVP (n = 20)	ES (Hedges' g)	Descriptor
IMTP (N)	3800.92 ± 618.07	3541.85 ± 523.94	0.44 (-0.14, 1.02)	small
SJ (cm)	47.70 ± 7.70	43.95 ± 6.11	0.52 (-0.06, 1.11)	small
DJ (cm)	45.50 ± 5.79	45.04 ± 6.33	0.07 (-0.50, 0.65)	trivial
CMJ (cm)	49.33 ± 8.49	46.61 ± 7.10	0.34 (-0.24, 0.91)	small
10m (s)	1.83 ± 0.15	1.78 ± 0.12	0.39 (-0.18, 0.97)	small
20m (s)	3.12 ± 0.20	3.04 ± 0.27	0.35 (-0.23, 0.93)	small
30m (s)	4.36 ± 0.24	4.34 ± 0.19	0.08 (-0.50, 0.66)	trivial
T-test (s)	8.60 ± 0.31	9.32 ± 0.47	1.83 (1.15, 2.52)	large
RFD _{-100ms} (N·s ⁻¹)	13421.46 4659.86	± 9882.55 ± 2535.92	0.89 (0.29, 1.50)	moderate
DSI (AU)	0.60 ± 0.09	0.63 ± 0.08	0.34 (-0.23, 0.92)	small
RSI (m·s ⁻¹)	2.08 ± 0.53	1.75 ± 0.47	0.63 (0.04, 1.22)	moderate
EUR (AU)	1.04 ± 0.11	1.06 ± 0.07	0.23 (-0.35, 0.80)	small

Abbreviations: IVP, indoor volleyball players; BVP, beach volleyball players; IMTP, isometric mid-thigh pull; SJ, squat jump; DJ, drop jump; CMJ, countermovement jump; T-test, T-test change-of-direction test; RFD_{-100ms}, rate of force development over the first 100 ms; DSI, dynamic strength index; RSI, reactive strength index; EUR, eccentric utilization ratio; ES, effect size (Hedges' g); AU, arbitrary units.

Notes: ES is reported as Hedges' g [95% CI]. Bold indicates a statistically significant between-group difference ($p < 0.05$). Descriptor is based on |g|: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (≥ 2.00)