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Association between pre-season lower limb interlimb asymmetry and non-contact lower limb injuries in elite male volleyball players

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This study aimed to quantify lower limb interlimb asymmetries in elite male volleyball players by assessing key performance measures, including vertical jumps, change of direction, and muscle strength. It further explored the potential association between these asymmetries and the occurrence of non-contact lower limb injuries. Thirty-one elite male volleyball athletes (age: 20.1 ± 1.2 years; training experience: 7.1 ± 2.2 years) participated in the study. Interlimb asymmetries were assessed using the single-leg countermovement jump (SCMJ), squat jump (SSJ), drop jump (SDJ), T-test, and Pro-test to evaluate lower limb power, agility, and change-of-direction ability. Concentric and eccentric strengths of the knee extensors and flexors were measured using isokinetic testing. Athletes were monitored for 8 months to record non-contact lower limb injuries. Significant variability was observed in the lower extremity interlimb asymmetries (ranging from 3.61 to 15.91%) across different tests ($P < 0.05$). Thirteen athletes sustained at least one non-contact lower limb injury during the follow-up period. Logistic regression analysis identified significant predictors of injury risk: knee extensor concentric normalized peak torque asymmetry (OR 1.64 [95% CI 1.14–2.37]; $P < 0.01$), SCMJ height asymmetry (OR 1.18 [95% CI 1.01–1.34]; $P < 0.05$), and T-test performance asymmetry (OR 1.41 [95% CI 1.07–1.85]; $P < 0.05$). Interlimb asymmetries in SCMJ, knee extensor strength, and T-test performance are significant risk factors for non-contact lower limb injuries in elite male volleyball players. Systematic evaluation of these asymmetries could contribute to targeted injury prevention strategies and optimized athletic performance.

Keywords Interlimb asymmetry, Lower limb functional performance, Sports injury, Volleyball athletes

Volleyball, a sport renowned for its enduring popularity, has witnessed a consistent increase in its fan base, evidenced by rising participation rates globally[1]. Since its inception over a century ago, volleyball has grown into one of the most widely played sports worldwide, with over 200 million participants[2,3], rivaling the 250 million soccer players reported by the Fédération Internationale de Football Association[4]. Despite being classified as a non-contact sport, volleyball is associated with a substantial incidence of musculoskeletal injuries, particularly affecting the lower extremities[5–7]. Notably, the prevalence of inter-limb asymmetries has been implicated as a significant factor, potentially impairing athletic performance and elevating the risk of injuries[8–10].

Volleyball demands dynamic and explosive maneuvers, typically encompassing 250–300 such movements per game, mainly consisting of 50–60% jumps, 27–33% attacking actions, and 12–16% landings[11]. These unilateral actions could lead team sport players to develop inter-limb asymmetries[12]. The biomechanics of a volleyball jump, crucial for practical force application and ball impact, involve synchronized leg propulsion balanced by the attacking arm's forward swing[13]. Additionally, the sport's characteristic landing mechanics, especially the unilateral landings that constitute 40% of all landings, significantly contribute to lateral muscular imbalances[14]. Additionally, certain zone-specific gestures, like blocking movements, are typically executed towards the same side[15]. Consequently, these repetitive actions during training sessions and competitive matches may contribute to developing asymmetries in volleyball players.

Previous research investigating interlimb asymmetries in volleyball players has yielded inconsistent findings. Studies have not consistently found contralateral differences in lower limbs when assessing asymmetry through bilateral isokinetic tests in German third-league players[11] or via a countermovement jump test (CMJ)

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in first-division Brazilian athletes[16]. However, other research indicates asymmetries exceeding 10% in players undergoing 6–10 h of training per week, as identified using single-leg CMJ assessments[17]. These discrepancies highlight the complexity of measuring and interpreting asymmetry in athletic populations and underscore the need for more comprehensive evaluation approaches[18,19].

Moreover, extensive research has clarified the relationship between interlimb asymmetry and injury risk, particularly through studies demonstrating significant correlations between asymmetrical jump performance, dynamic balance, and knee strength, all of which influence non-contact lower limb injury occurrence[20–22]. For instance, Warren et al.[23] reported that athletes with marked asymmetries in unilateral hopping tests faced an increased injury risk. Additionally, often assessed through the Star Excursion Balance Test (SEBT) and its derivative, the Y Balance Test (YBT), has shown that interlimb asymmetry of ≥ 4 cm is associated with higher injury risk[20,24]. Gonell et al.[25] demonstrated that soccer players with a ≥ 4 cm asymmetry in the YBT posteromedial direction were 3.86 times more likely to sustain a lower extremity injury, while Hartley et al.[26] found a 3.64 times greater risk of ankle sprain in collegiate male athletes with normalized YBT anterior reach scores of ≤ 54.4%.

Despite this growing body of evidence, existing research has focused predominantly on upper limb asymmetries in volleyball players, often overlooking the lower limbs, despite their critical role in the sport's biomechanical demands[1,6,7,27]. Notably, a study involving 295 Danish volleyball players reported that 55% had sustained at least one knee injury, and 48% had chronic knee complaints[2]. Furthermore, athletes with over 11.5 years of experience were shown to be at higher risk for overuse injuries[1].

In summary, although the high prevalence of lower-limb injuries in volleyball, research on lower-limb asymmetries and their role in injury susceptibility remains limited. While previous studies have extensively examined upper limb asymmetries, the extent to which interlimb asymmetries in the lower body contribute to non-contact injury risk has not been fully established. Moreover, existing findings on lower limb asymmetries in volleyball are inconsistent—some studies report significant interlimb imbalances, while others find minimal differences depending on the assessment method used. This lack of consensus highlights the need for a more comprehensive evaluation of lower limb asymmetries using multiple performance tests. By addressing this gap, our study aims to provide a clearer understanding of the role of asymmetry in volleyball-specific movements and its implications for injury prevention. The insights derived from this study will help guide the development of targeted training and injury prevention strategies, ultimately enhancing the safety and performance of volleyball athletes.

Methods

Study design and participants

This study employed a prospective cohort design involving 31 elite male volleyball players. A priori power analysis was conducted using G*Power 3.1.9.2 to determine the required sample size for a bivariate correlation analysis. The effect size (0.48) was selected based on prior research[28]. The study was performed using a two-tailed test, with a significance level (α) set at 0.05 and a statistical power (1 − β) of 0.80, ensuring an 80% probability of detecting an actual effect if present. The results indicated that a minimum sample size of 31 participants was required to achieve the desired power.

All athletes and their coaches were informed about the purpose and requirements of the tests. The study followed the guidelines of the Helsinki Declaration, and all participants provided written informed consent before participating in the research protocol (Table 1). The Ethics and Ethics Committee of the Capital University of Physical Education and Sports approved this study (Approval Number: 2023A075).

The inclusion criteria were a minimum of three years of regular volleyball training (≥ 3 sessions per week) and an age of ≥ 18 years. Participants were excluded if they had any of the following conditions at the time of testing or within the previous 6 months: A history of surgical intervention in the lower limbs within the past 12 months. Any acute musculoskeletal injury affecting the lower limbs that resulted in more than 2 weeks of restricted training or competition in the past 6 months[28]. A diagnosis of chronic pain syndromes, including patellofemoral pain syndrome, Achilles tendinopathy, or chronic ankle instability, significantly impaired athletic performance: any neuromuscular disorder or systemic condition affecting movement or motor control.

Experimental design

A within-day repeated-measures design was employed to assess the reliability of the test, following a descriptive approach[29]. Each volleyball player completed three repeated trials of the test on the same day, with sufficient recovery periods between trials to minimize fatigue effects. This design ensured the measurements were consistent and reflected the athlete's typical performance.

The three measurements' best value was used to analyze the possible relationships between the tests. The evaluation of the symmetry and performance tests was done d at the beginning of the 2023 pre-season, where they competed weekly (four training sessions and the competition match). The battery of tests included the following six assessments of muscle asymmetries: Power ability was evaluated through vertical jumping tests, including single-leg squat jumps (SSJ), single-leg countermovement jumps (SCMJ), and single-leg drop jumps (SDJ); change-of-direction ability was assessed through the T-test and Pro-test; and muscular strength

Age/year	Height/cm	weight/kg	Lower limb length/cm	training experience/year
20.1 ± 1.2	191.4 ± 6.1	81.2 ± 10.6	96.6 ± 5.0	7.1 ± 2.2

Table 1. Anthropometric data for participants.

imbalances were measured using knee isokinetic testing at an angular velocity of 60°/s. These assessments have been validated in prior studies for their effectiveness in detecting lateral asymmetry among athletes from various sports, including volleyball[30]. All participating athletes were familiar with the testing procedures prior to the study. The tests were administered across three distinct sessions, following the methodological recommendations of Baechle and Earle[31]. In the first session, the SSJ, SCMJ, and SDJ tests were performed. In the second session, knee isokinetic strength testing was conducted. All participants completed the tests in the specified order to maintain consistency and control for potential fatigue effects.

Procedure

Injury surveillance

Participants were monitored for non-contact lower limb injuries for 8 months following baseline assessments. The injury was defined as "any damage to a body part sustained during volleyball, resistance training, or other conditioning activities that interfered with training and/or competition." This definition was adapted from previous research to capture injuries of all severities, including those that may not result in complete training cessation but could still impact athletic performance[32,33]. A strict time-loss definition (i.e., requiring missed training days) may underestimate less severe injuries that, while permitting continued participation, often necessitate exercise type, range of motion, training volume, or intensity modifications. Given that even minor injuries can influence long-term athletic development, this study adopted a broader definition to provide a more comprehensive evaluation of its impact on training adaptation and injury prevention strategies in elite volleyball players.

Team coaches documented all incidents using a standardized injury report form, based on templates from prior studies[33,34]. To ensure accuracy and consistency, the research team verified each reported injury and classified it as a lower extremity medical condition sustained during non-contact volleyball activities that impeded the athlete's ability to fully participate in training or competition[35]. Injuries resulting from direct contact with other players, equipment (e.g., net posts), or surface impact (e.g., floor contact contusions) were excluded from the analysis. In cases where a participant sustained multiple injuries, only the first recorded injury was included in the analysis to avoid confounding effects from subsequent injuries[36]. The study's research coordinator collected the completed injury reports from the coaches and athletic trainers on a quarterly basis for data verification and analysis.

Vertical jumping tests

The participants performed vertical jump tasks (SSJ, SCMJ, and SDJ), and the order of the tasks was randomized. Before the measurements, participants completed a 15-min warm-up, which included 10 min of treadmill running at a pace of 8 km/h (5 mph), followed by 5 min of dynamic stretching exercises and 5 min of low-intensity bodyweight resistance exercises, such as squats and lunges.

Each jump task (SSJ, SCMJ, and SDJ) was performed on force platforms (Kistler 9281CA; Winterthur, Switzerland). Prior studies have demonstrated outstanding reliability in evaluating SCMJ and SSJ with Intraclass Correlation Coefficients (ICCs) ranging from 0.927 to 0.980, from 0.832 to 0.992, respectively[37,38]. And this methodology for the drop vertical jump has also demonstrated high reliability in attaining the variables of interest and was replicated by Paterno et al.[39]. The participants performed 2–3 familiarization jumps with submaximal effort, after which three repetitions were recorded for each leg jump. Rest periods were set at 1 min between repetitions and 2 min between jump legs and jump tasks, respectively. The order of the jump tasks was randomized for each participant. For SSJ and SCMJ, the hands were placed on the ipsilateral hip and kept in this position throughout the jump. SSJ was performed with the participant descending to the starting position, which was achieved when the knee angle of the supporting leg was 90°. After stabilizing for 2–3 s, the jump was performed without countermovement. To ensure that, the examiner inspected the force–time curve on the computer after each repetition, and the jump was repeated in case any countermovement was visually discriminable (note that the software allowed zooming in for a close inspection). Regarding the SCMJ, the participants were instructed to jump as high as possible by performing a fast countermovement (to the point where the knee angle of the supporting leg was at 90° and then immediately pushing off and extending forcefully through the hips, knees, and ankles[40]. Before each CMJ, participants were required to squat controlled until the desired position was reached to become familiarized with the 90° knee angle position, which was previously determined with a manual goniometer. For the SDJ, subjects stand on a 15 cm high box with their hands on their ipsilateral hip. They take a small step forward, then jump down with their feet together, keeping their hips, knees, and ankles straight to avoid bending during the descent. Upon contact with the force platform, they quickly jump upward while maintaining straight knees[41].

Data was captured at 1000 Hz through BioWare software (Version: 5.3.2.9, Kistler 9281CA, Switzerland) and then imported into V3D (V6 Professional, C-motion, Germantown, Maryland, USA). A fourth-order 15 Hz low-pass filter was employed to process the data, and jump height (cm) for SCMJ, SSJ, and SDJ were subsequently computed. Jump height was determined using the formula: $0.5 \times 9.81 \times (\text{flight time}/2)^2$[42].

Change of direction tests

Before each change of direction measurement, the participants performed a 15-min warm-up, consisting of 10 min of treadmill running at a pace of 8 km/h, 5 min of dynamic stretching exercises, and 5 min of short (e.g., 5, 10, 15-m) sprints with submaximal effort.

The T-test was conducted using a standardized version as reported in previous literature[43]. The measurements were converted from yards to meters, forming a distance of 10 × 10 m. The testing route employed in this study was based on the work of Miller et al. (Fig. 1)[44]. Throughout the testing procedure, participants continuously faced forward. The timing gates (Smart Speed; Fusion Sport Pty Ltd, Australia) were placed 0.75 m above the

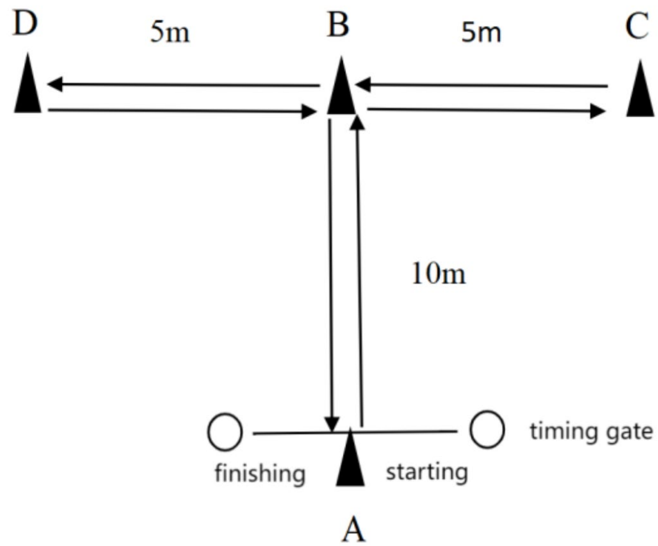

Fig. 1. Schematic representation of T-test.

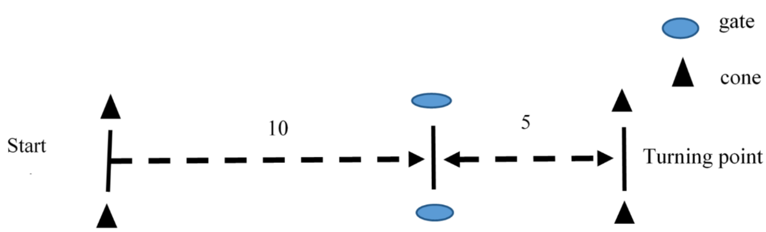

Fig. 2. Schematic representation of Pro Test.

synthetic track and on either side of the starting line, with a 3 m separation between them. Timing started when the participants passed through the timing gates and stopped when they returned to the finish line. Three trials were conducted, with a rest interval of 2–3 min between each trial, and the best performance was recorded.

The Pro test, also called the 5–0–5 test, demonstrated substantial reliability, indicated by an Intraclass Correlation Coefficient (ICC) of 0.876 and a Coefficient of Variation (CV) of 2.3%[45]. Before the test, a distance of 15 m was delineated with cones marking the start and end points. At 10 m from the beginning, two SmartSpeed PT electronic timing gates (Fusion Sport Pty Ltd, Australia) were set up (Fig. 2). Each participant was required to touch the line with their foot and hand of the tested side, and the sequence of participants and tested foot was randomized. The timing started as the participant passed through the first gate at the 10-m mark and stopped after the athlete completed the turn and returned through the gate. Three trials were conducted, with a rest interval of 2–3 min between each trial, and the best performance was recorded.

Lower limb strength test

Before measuring, the players completed general warm-up exercises, including running on a running machine for 5 min at 8 km/h, and 5 min dynamic stretching exercises, including a downward dog, walking quad, and word's most excellent stretch. The unilateral strength of the concentric and eccentric action of the knee extensors and flexors was measured using an isokinetic dynamometer ISOMED 2000 (D. & R. Ferstl GmbH, Hemau, Germany).

Angular velocities of 60° s^{-1} were used for knee unilateral strength. The test modes were chosen "as concentric, concentric," and "eccentric, eccentric." Previous research has shown excellent reliability for assessing peak torque when assessing flexion and extension concentrically and eccentrically at 60°/s (ICC = 0.93–0.95)[46]. For the knee joint test, the upper body was fixed with straps; the athlete was in a sitting position, the upper body and thighs were fixed with straps; the subject's hands gripped the handles on both sides of the test chair, the axis of the rotation of the dynamometer was aligned with the lateral condyle of the femur, and the lower edge of the pad of the dynamometer arm was fixed in the calf at a distance of 2–3 cm from the lateral condyle of the ankle joint. The range of motion was set to 10–90°of knee (0° = the foot was perpendicular to the calf).

The testing protocol consisted of one set for 60° s^{-1} of the knee. In the warm-up set, the players performed three concentric or eccentric reciprocal actions with a progressive rise in the muscle action until a maximum action was performed. After a 30-s rest, the players performed (i) five consecutive concentric quadriceps and hamstring contractions and (ii) five eccentric quadriceps and hamstring contractions. There was a 3-min interval between testing legs and a 5-min interval between testing modes[47]. The players received concurrent visual feedback during the testing through an isokinetic strength curve displayed on the dynamometer monitor. Normalized peak torque (PT, Nm/kg) was used to analyze the players' weight.

Statistical analyses

This study initially documented all data as mean values and standard deviations using Microsoft Excel and transferred to IBM SPSS Statistics version 23.0 (IBM Corp, Armonk, NY, USA) for advanced analysis. The Shapiro–Wilk test assessed the normality of the data distribution. Non-normally distributed data underwent square root transformation before further examination. Performance discrepancies between limbs were evaluated using paired-sample t-tests. At the same time, effect sizes were derived from pairwise comparisons, categorized as small (< 0.2), moderate (0.2–0.5), and large (> 0.8) according to the mean differences standardized by the pooled standard deviation[48]. Independent t-tests scrutinized the performance and asymmetry variations between injured and non-injured athletes, considering only asymmetries with P-values < 0.05 for subsequent analysis. Variables demonstrating significant disparities in opposing samples t-tests underwent Spearman's correlation analysis regarding injury, retaining only those with notable differences for the following steps. The final analysis was binary logistic regression analysis tests to identify risk factors. Asymmetries were calculated for all tasks defining the dominant (D) (the limb with the better functional test) and ND limb, using the following formula: asymmetry index = (D − ND)/D × 100[8]; as the level of significance was set to $P < 0.05$, refers to the statistical significance threshold used to determine whether the observed differences in interlimb asymmetries across different tests were significant. Specifically, this indicates that the variability in lower extremity interlimb asymmetries across different tests was statistically significant.

Results

In the 8-month follow-up study, 31 male volleyball athletes aged 18 to 22 were followed, as shown in Table 2. Thirteen athletes sustained noncontact lower limb injuries, with an average age of 20.15 ± 1.35 years, height of 190.38 ± 6.935 cm, body weight of 79.69 ± 12.59 kg, and training experience of 8.08 ± 2.72 years. Conversely, the 18 uninjured athletes had an average age of 20 ± 1.03 years, height of 192.11 ± 5.44 cm, body weight of 82.22 ± 9.14 kg, and training experience of 6.39 ± 1.42 years. The most frequent injury types were muscle strains and sprains, predominantly affecting the ankle (30%) and knee (23.1%). Most (69.2%) of the injuries occurred on the nondominant leg, while 30.8% were on the dominant leg. Statistical analysis revealed no significant differences in demographics or physical characteristics between the injured and uninjured groups ($P > 0.05$).

Table 3 shows the functional performance of the D and ND limbs and the percentage of asymmetry for each task. Significant differences between D and ND limbs were found across all the tasks ($p < 0.001$). The mean unilateral asymmetries ranged between 15.91% (D_KEE_PT) and 3.61% (ND_PRO test).

Table 4 and Fig. 3 present an independent t-test analysis of knee isokinetic performance at 60°/s, comparing injured with non-injured athletes. Significant distinctions were observed in the dominant knee extensor's concentric and eccentric normalized peak torque. Specifically, the interlimb asymmetry indices demonstrated marked differences, with injured athletes showing 15.96 ± 5.41% compared to 7.11% ± 4.10% in non-injured athletes for the knee extensor's concentric normalized peak torque, with $P < 0.01$. The analysis of the knee extensor's and flexor's eccentric and eccentric normalized peak torque indicated notable differences; however, the significant interlimb asymmetries were confined to the knee extensor's normalized concentric peak torque.

Table 5 details the analysis of change of direction performance through an independent t-test, contrasting injured athletes with their non-injured counterparts. The results indicated no statistically significant difference in the same-limb change of direction performance across both groups. However, Fig. 4 elucidates the disparities in the interlimb asymmetry indices during change of direction tests. It was found that the injured athletes exhibited significantly greater asymmetry indices than non-injured athletes in both the Pro and T-tests, with the Pro test showing asymmetry indices of 10.77 ± 3.47% for injured athletes compared to 8.00 ± 2.61% for non-injured, and the T-test revealing indices of 5.83 ± 4.31% for injured versus 5.78 ± 3.08% for non-injured athletes, respectively.

Table 6 shows the analysis of vertical jump performance through an independent t-test, contrasting injured athletes with their non-injured counterparts. The results also indicated no statistically significant difference in the same-limb vertical jump performance across both groups. However, Fig. 5 elucidates the disparities in the interlimb asymmetry indices during vertical jump tests. It was found that the injured athletes exhibited significantly greater asymmetry indices than non-injured athletes in vertical jump tests, with the SSJ test showing

	Injured Athletes		Non-injured Athletes		
	n	Mean ± SD	n	Mean ± SD	*P*
Age, year	13	20.15 ± 1.35	18	20 ± 1.03	0.176
Height, cm	13	190.38 ± 6.94	18	192.11 ± 5.44	0.309
Body weight, kg	13	79.69 ± 12.59	18	82.22 ± 9.14	0.560
Training experience, year	13	8.08 ± 2.72	18	6.39 ± 1.42	0.090

Table 2. Characteristics of athletes.

Performance test	Mean ± SD	Mean difference	95% CI	ES	Asymmetry (%)
D_KFC_PT(Nm/kg)	1.58 ± 0.32**	0.12 ± 0.12	0.07–0.16	0.27	7.34 ± 5.91
ND_KFC_PT(Nm/kg)	1.50 ± 0.28				
D_KEC_PT(Nm/kg)	2.88 ± 0.73**	0.32 ± 0.22	0.25–0.40	0.44	10.82 ± 6.40
ND_KEC_PT(Nm/kg)	2.55 ± 0.62				
D_KFE_PT(Nm/kg)	2.72 ± 0.78**	0.32 ± 0.26	0.22–0.41	0.45	11.07 ± 7.2
ND_KFE_PT(Nm/kg)	2.40 ± 0.64				
D_KEE_PT(Nm/kg)	1.77 ± 0.53**	0.29 ± 0.22	0.21–0.37	0.58	15.91 ± 10.5
ND_KEE_PT(Nm/kg)	1.48 ± 0.47				
ND_T test(s)	10.80 ± 0.84**	0.76 ± 0.48	0.58–0.94	0.95	7.90 ± 4.64
D_T test(s)	10.04 ± 0.76				
ND_PRO test(s)	2.61 ± 0.16**	0.13 ± 0.12	0.09–0.18	0.93	3.61 ± 0.06
D_PRO test(s)	2.47 ± 0.14				
D_SSJ(m)	0.18 ± 0.03**	0.02 ± 0.01	0.01–0.02	0.85	11.88 ± 4.00
ND_SSJ(m)	0.16 ± 0.03				
D_SCMJ(m)	0.20 ± 0.03**	0.02 ± 0.01	0.02–0.03	1.00	9.86 ± 9.09
ND_SCMJ(m)	0.17 ± 0.02				
D_SDJ(m)	0.19 ± 0.04**	0.02 ± 0.01	0.02–0.03	0.50	11.35 ± 4.44
ND_SDJ(m)	0.17 ± 0.04				

Table 3. Interlimb functional performance tests and asymmetry. D, stronger leg; ND, weaker leg; KFC_PT, knee flexor's normalized concentric peak toque; KEC_PT, knee extensor's normalized concentric peak toque; KFE_PT, knee flexor's normalized eccentric peak toque; KEE_PT, knee extensor's normalized eccentric peak toque; SSJ, single leg squat jump; SCMJ, single leg counter movement jump; SDJ, single leg drop jump ; $^{**}P < 0.01$.

Performance test	Injured	Non-injured	*P*
D_KFC_PT(Nm/kg)	1.63 ± 0.31	1.54 ± 0.33	0.44
ND_KFC_PT(Nm/kg)	1.48 ± 0.24	1.44 ± 0.32	0.68
D_KEC_PT(Nm/kg)	3.22 ± 0.75	2.64 ± 0.61	0.02
ND_KEC_PT(Nm/kg)	2.71 ± 0.68	2.45 ± 0.57	0.25
D_KFE_PT(Nm/kg)	3.10 ± 0.83	2.45 ± 0.61	0.02
ND_KFE_PT(Nm/kg)	2.65 ± 0.66	2.22 ± 0.57	0.06
D_KEE_PT(Nm/kg)	1.98 ± 0.53	1.62 ± 0.49	0.06
ND_KEE_PT(Nm/kg)	1.67 ± 0.44	1.35 ± 0.45	0.06

Table 4. Descriptive raw data for isokinetic knee strength tests across injured and non-injured athletes. D, stronger leg; ND, weaker leg; KFC_PT, knee flexor's normalized concentric peak toque; KEC_PT, knee extensor's normalized concentric peak toque; KFE_PT, knee flexor's normalized eccentric peak toque; KEE_PT,knee extensor's normalized eccentric peak toque; $^{*}P < 0.05$; $^{**}P < 0.01$.

asymmetry indices of 12.57 ± 4.34% for injured athletes compared to 7.89 ± 4.42% for non-injured and the SCMJ revealing indices of 14.88 ± 2.76% for injured versus 9.72 ± 3.39% for non-injured athletes, respectively.

Moderate to strong positive correlations were observed between lower extremity asymmetrical functional performance and lower limb non-contact injuries, as illustrated in Fig. 6. Specifically, the asymmetry indices for the knee extensor's concentric normalized peak torque (KEC_AI), T-test (T_AI), and single-leg countermovement jump (SCMJ_AI) were all significantly correlated with injury status (r = 0.709, 0.604, and 0.418, $P < 0.05$, respectively), indicating that more significant asymmetry in these measures was associated with a higher likelihood of injury. While significant differences were noted in single-leg squat jump (SSJ_AI) and Pro test (PRO_AI) asymmetry indices between injured and non-injured athletes, their correlations with injury status were not statistically significant. Additionally, Fig. 6 displays interrelationships among different asymmetry indices, showing that knee extensor asymmetry (KEC_AI) was moderately correlated with both T-test asymmetry (r = 0.419, $P < 0.05$) and SCMJ asymmetry (r = 0.490, $P < 0.01$), suggesting potential shared neuromuscular imbalances. These findings highlight that specific lower limb asymmetries (particularly in knee extensor strength, agility, and jump performance) are more strongly associated with injury risk. In contrast, other asymmetry measures may not independently predict injury.

Logistic regression analysis (Table 7) demonstrated that interlimb asymmetries, specifically in the knee extensor's concentric normalized peak torque (OR 1.64 [95% CI 1.14–2.37]; $P < 0.01$), SCMJ (OR 1.18 [95% CI 1.01–1.34]; $P < 0.05$), the T-test (OR 1.41 [95% CI 1.07–1.85]; $P < 0.05$), significantly contribute as risk factors

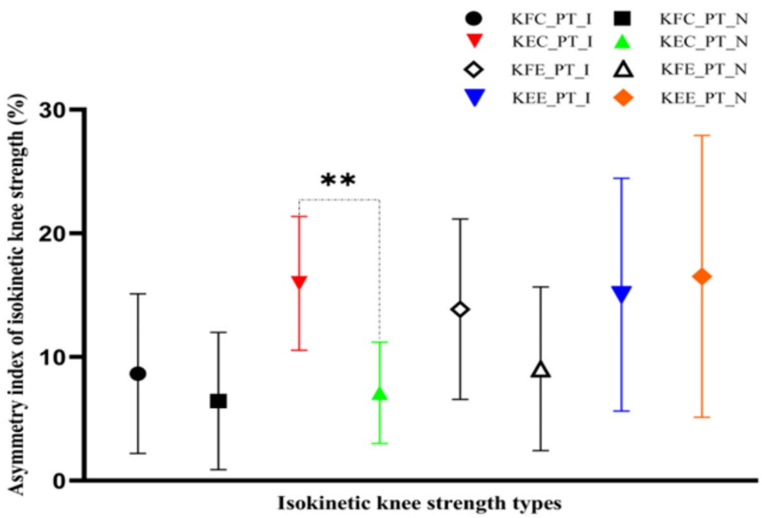

Fig. 3. Interlimb Asymmetry of Isokinetic Knee Strength between Injure and Non-injured Athletes. I, injured athletes; N, Non-injured athletes; D, stronger leg; ND, weaker leg; KFC_PT, knee flexor normalized concentric peak toque; KEC_PT, knee extensor normalized concentric peak toque; KFE_PT, knee flexor normalized eccentric peak toque; KEE_PT, knee extensor normalized eccentric peak toque; $^*P<0.05$; $^{**}P<0.01$.

Performance test	Injured	Non-injured	*p*
ND_T test(s)	9.81 ± 0.70	10.21 ± 0.77	0.15
D_T test(s)	10.87 ± 0.92	10.75 ± 0.80	0.69
ND_Pro test(s)	2.61 ± 0.17	2.61 ± 0.16	0.91
D_Pro test(s)	2.45 ± 0.19	2.49 ± 0.11	0.49

Table 5. Descriptive raw data for change of direction tests based on injury status.

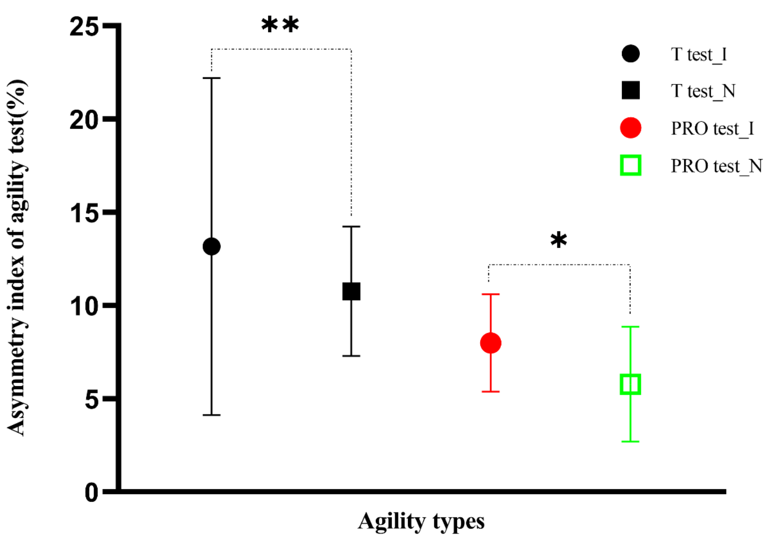

Fig. 4. Interlimb Asymmetry of Change of Direction Tests between Injured and Non-injured Athletes. I, injured athletes; N, non-injured athletes, D, stronger leg; ND, weaker leg; $^*P<0.05$; $^{**}P<0.01$.

Performance test	Injured	Non-injured	*p*
D_SSJ(m)	0.19 ± 0.03	0.18 ± 0.03	0.15
ND_SSJ(m)	0.17 ± 0.03	0.16 ± 0.03	0.56
D_SCMJ(m)	0.21 ± 0.03	0.19 ± 0.02	0.08
ND_SCMJ(m)	0.18 ± 0.03	0.17 ± 0.02	0.42
D_SDJ(m)	0.20 ± 0.03	0.19 ± 0.04	0.50
ND_SDJ(m)	0.17 ± 0.03	0.17 ± 0.04	0.95

Table 6. Descriptive raw data for vertical jump tests in injured and non-injured athletes. D, stronger leg; ND, weaker leg; SSJ, single leg squat jump; SCMJ, single leg counter movement jump; SDJ, single leg drop jump.

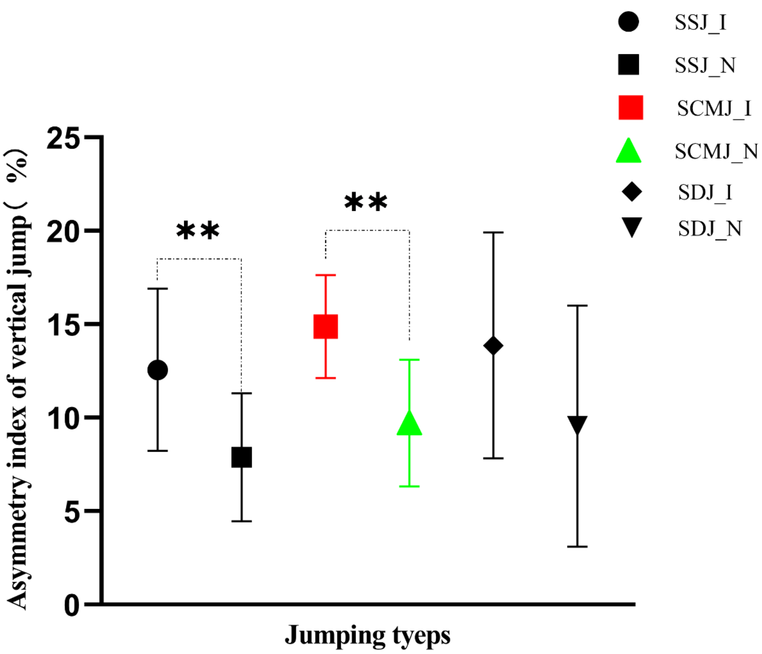

Fig. 5. Interlimb Asymmetry of Vertical Jump Tests between Injure and Non-injured Athletes. I, injured athletes; N, non-injured athletes; D, stronger leg; ND, weaker leg; SSJ, single leg squat jump; SCMJ, single leg counter movement jump; SDJ, single leg drop jump; $^{*}P < 0.05$; $^{**}P < 0.001$.

for non-contact lower limb injuries. The model demonstrated minimal interdependency among predictors, ensuring unique contributions to the injury risk assessment.

Discussion

This study aimed to quantify lower limb interlimb asymmetries in elite young male volleyball players by assessing performance in unilateral vertical jumps, agility tests, balance assessments, and isokinetic muscle strength tests. Subsequently, it examined the association between these asymmetries and the occurrence of non-contact lower limb injuries. Results revealed varying degrees of asymmetry across the different tests, with isokinetic strength assessments showing the most significant discrepancies. Unilateral vertical jumps exhibited greater interlimb imbalances compared to change-of-direction tests. Furthermore, increased asymmetry in knee extensor normalized concentric peak torque, T-test performance, and single counter movement jump was significantly associated with a higher incidence of non-contact injuries.

Our study thoroughly analyzed lower limb interlimb asymmetries in elite male volleyball players, with a specific emphasis on single-leg knee isokinetic strength comparison between dominant and non-dominant legs. Significant inter-limb asymmetry was observed in knee extensor isokinetic strength, with concentric strength values at 10.82 ± 6.40% and eccentric strength values at 11.07 ± 7.2%. These results align with previous studies by[16,40,49]. Furthermore, our study revealed notable asymmetries in knee flexor concentric and eccentric strengths, with values of 11.07 ± 7.2% and 15.91 ± 10.5%, respectively. While similar to findings by Hadzic et al.[50] (13.6 ± 12.0% and 14.7 ± 10.9%, respectively), our research highlighted a distinct variance in the inter-limb asymmetry index, particularly in eccentric isokinetic strengths. This discrepancy may be attributed to our methodological approach, where leg dominance was determined based on performance scores rather than the traditional assumption of right-leg dominance. The age diversity among the athletes studied further adds context

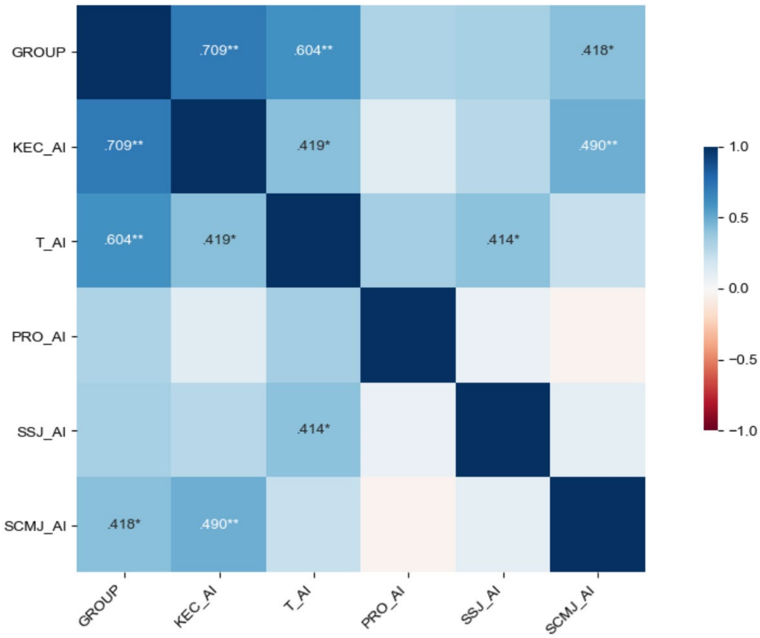

Fig. 6. Correlation between Lower Limb Asymmetry Measures and Injury status (injured vs. non-injured athletes). Injured vs. non-injured athletes; AI, asymmetry index; T, T test; PRO, Pro test; KFC, knee flexor normalized concentric peak toque; KEC,knee extensor normalized concentric peak toque; SSJ,single leg squat jump; SCMJ,single leg countermovement jump; $^{*}P<0.05$; $^{**}P<0.01$.

Performance test	OR	95% CI		*P*
KEC_AI	1.64	1.14	2.37	0.01
SCMJ	1.18	1.01	1.34	0.03
T_AI	1.41	1.07	1.85	0.02

Table 7. Risk factors in predicting noncontact in jury. AI, asymmetry index; T,T test; KEC, knee extensor's normalized concentric peak toque; SCMJ, single leg counter movement jump; $^{*}P<0.05$; $^{**}P<0.01$.

to our results, suggesting that developmental and training-related factors could play a role in the observed asymmetries.

Our investigation into vertical jump asymmetries revealed results for SSJ: 11.88 ± 4.00%, SCMJ: 9.86 ± 9.09%, and SDJ: 11.35 ± 4.44%, consistent with previous studies. These findings align with research in various sports disciplines, showing a range of SCMJ asymmetries: 8.56 ± 7.3% to 10.24 ± 9.39% in young volleyball players[40,51], 10.40 ± 10.80% in team sport athletes[52], 14.11 ± 8.6% in female basketball players[17], 12.54 ± 10.8% in youth female soccer players, and 8.65 ± 5.98 to 9.16 ± 5.87% in adult female soccer players[19,53]. Our study findings align with previous data on volleyball players. The change of direction performance asymmetry observed in our study (T-test: 7.90 ± 4.64%, Pro-test: 3.61 ± 0.06%) was similar to that reported by Hart et al. (2014) (8.2 ± 0.2%)[54]. Lockie et al.[52] also noted a 5–10% performance deficit between limbs in Australian footballers, with all players showing a directional preference. The change of direction test results indicated a minimal level of asymmetry compared to the jump tests, consistent with previous studies[17,45]. The significance of linear speed in these assessments is worth noting, as it may obscure existing asymmetries in a change of direction task[55].

Our study identified a significant correlation between lower limb functional imbalance and sports injuries in volleyball players. A bilateral asymmetry exceeding 10–15% was associated with an increased risk of injury. Specifically, our analysis showed a notable difference in knee extensor and flexor peak torque between injured (15.96 ± 5.41%) and non-injured (7.11% ± 4.10%) volleyball athletes[46,56–58]. A notable imbalance in knee extensor and flexor normalized peak torque was observed between volleyball athletes with and without injuries (injured: 15.96 ± 5.41%; non-injured: 7.11% ± 4.10%, respectively). Furthermore, binary logistic regression analysis indicated that for every 1% increase in the interlimb asymmetry of knee extensor concentric normalized peak torque, the risk of non-contact lower limb injuries rose by 1.64 times (OR 1.64, 95% CI [1.14, 2.37], $p<0.01$). This suggests that knee extensor strength asymmetry may be a key predictor of injury risk, likely due to the specific unilateral jumping and landing demands in volleyball[11]. Repetitive movements, such as dominant-limb takeoff in attacks and single-leg landings from blocks, contribute to habitual loading asymmetries, reinforcing strength imbalances over time[59]. As a result, landing mechanics may be compromised, leading to more significant knee valgus, external tibial rotation, and hip adduction, all well-documented risk factors for lower limb injuries[60].

Studies have shown that occasional unilateral landings can significantly increase the likelihood of knee ligament injuries[61], requiring the landing limb to absorb forces normally distributed across both legs[60]. When knee extensor strength asymmetry is present, the weaker limb may fail to properly stabilize the knee during impact absorption properly, increasing compensatory loading on the dominant limb and leading to overuse injuries and more significant ligament stress[62]. In particular, an athlete landing with a forward-flexed and rotated trunk, hip adduction, knee valgus positioning, and poor opposite limb control may strain the quadriceps and supporting structures, making injury more likely. Since quadriceps function is crucial for energy dissipation during landing, strength imbalances may impair this process, further elevating the risk of patellofemoral pain, ACL injuries, and chronic instability. Given these findings, addressing knee extensor strength asymmetry through targeted neuromuscular training, bilateral strength balance, and eccentric control exercises may help reduce injury susceptibility in elite volleyball players.

Furthermore, our investigation revealed a significant difference in jump performance asymmetry between injured and non-injured athletes (14.88 ± 2.76% vs. 9.72 ± 3.39%, respectively; $P<0.001$), aligning with extant literature. Fort-Vanmeerhaeghe et al.[63] identified that asymmetry in injured athletes was substantially elevated compared to their non-injured counterparts, with a notable difference between genders (injured males: 17.1 ± 13.3%, females: 12.8 ± 6.2% vs. non-injured males: 9.7 ± 8.3%, females: 7.7 ± 5.6%). Consistently, Guan et al.[64] observed analogous patterns in young male taekwondo practitioners (injured: 17.07% vs. non-injured:8.66%). Moreover, our binary logistic regression suggests that an incremental 1% rise in interlimb asymmetry magnifies the odds of sustaining non-contact lower limb injuries by 1.18 times (OR 1.18, 95% CI [1.01, 1.34], $P<0.01$). Given the sport's reliance on unilateral takeoffs and landings, athletes with significant asymmetries may experience altered neuromuscular control and force distribution, predisposing them to non-contact lower limb injuries. The weaker limb's diminished ability to generate and absorb forces may lead to compensatory landing mechanics, increasing stress on the knee and ankle joints[63].

This study is the first to identify a significant correlation between T-test asymmetry ($p<0.001$) and the risk of non-contact lower limb injuries. Previous research has indicated that directional changes may trigger non-contact anterior cruciate ligament (ACL) injuries[65–67]. This could be due to an uneven distribution of forces across the knee joint, increasing the biomechanical load on the weaker limb. The intensified loading during directional shifts, especially in the presence of biomechanical deficits and 'high-risk' movement patterns such as lateral trunk flexion, knee valgus[68,69], extended knee positions[70], wide foot placements[69,71,72], and elevated ground reaction forces during change-of-direction tasks, may contribute to ACL injury risk. Therefore, recognizing asymmetry in athletes during change-of-direction tests is essential for preventing ACL injuries[73].

While our findings highlight the relationship between lower limb asymmetry and non-contact injury risk in elite male volleyball players, similar associations have been observed in other populations. Eagle et al.[74] examined bilateral quadriceps strength asymmetry in military unique tactics operators, demonstrating that individuals with prior knee injuries exhibited significantly greater asymmetry. This suggests that muscular imbalances may elevate injury susceptibility in sports settings and high-demand occupational environments, where asymmetry-related deficits could impair performance and increase injury risk. However, compared to volleyball, where repetitive unilateral jumps and landings contribute to asymmetry development, military operators experience high-impact load-bearing activities, which may influence the mechanism of asymmetry-related injuries differently. Similarly, Koźlenia et al.[75] investigated force, power, and morphological asymmetries in physically active men and women, identifying significant correlations between interlimb imbalances and injury risk. Their findings reinforce the broader impact of asymmetry beyond volleyball, suggesting that lower limb imbalances may contribute to injury susceptibility across multiple sporting disciplines. However, unlike volleyball players, whose asymmetries may arise from sport-specific movement patterns, asymmetries in general physically active populations may stem from habitual movement patterns, prior injuries, or training backgrounds. These comparisons suggest that lower limb asymmetries are a relevant injury risk factor across different populations, though the mechanisms and consequences may vary depending on sport-specific or occupational demands. Future research should explore whether targeted interventions to correct asymmetries can be generalized across different athletic and occupational settings or if they require sport-specific modifications based on unique movement demands.

The study identifies several limitations. Firstly, it focused solely on male volleyball players, potentially limiting the generalizability of the findings. Additionally, distinguishing injury occurrence between stronger and weaker legs poses a methodological constraint, as the definition of the stronger leg may vary across different tests. Another significant limitation is the unaccounted variation due to exposure time, an extrinsic factor that was difficult to standardize in practice. Despite these limitations, the study maintains a level of reliability in its findings as the training conditions were consistent among participants—they were all part of the same team, participated in identical volleyball games, and followed a uniform training schedule of 2 h per day, 3 days per week. While this study focused on the impact of lower limb functional asymmetry on non-contact lower limb injuries in volleyball players, future research could broaden its scope to explore the relationship between upper limb functional asymmetry and the risk of sports injuries in this athletic population.

Conclusion

This study delineates a significant correlation between pre-season lower limb interlimb asymmetries and the prevalence of non-contact lower limb injuries among elite male volleyball players, shedding light on the intricate relationship between specific asymmetries and injury risk. Our analysis indicates a notable range of interlimb asymmetries across varied functional performance tests, from 3.61 to 15.91%. Among these, the knee extensor's concentric normalized peak torque, T-test performance, and SCMJ asymmetry were significantly associated with volleyball injury risk, highlighting the complex interplay between biomechanical imbalances and sport-specific demands in injury occurrence. Mainly, knee extensor strength reflects the unilateral demands inherent in volleyball, with its repetitive high-impact jumping and landing actions. This specificity accentuates the risk of musculoskeletal imbalances and injuries, underlining the importance of preventive strategies tailored to volleyball's unique physical requirements. Additionally, the study links change of direction interlimb asymmetry with ACL injury risks, suggesting that uneven force distribution during rapid movements can exacerbate biomechanical stresses, particularly on the weaker limb.

Our findings advocate integrating interlimb asymmetry assessments into routine athletic screenings, allowing early identification and targeted intervention to mitigate injury risks. This approach not only promises to enhance performance and safety in volleyball but also posits a broader application across various sports, urging future research to explore the universal applicability of these insights. This research paves the way for advanced preventive strategies, emphasizing comprehensive, sport-specific evaluations and fostering a safer sporting environment across disciplines.

Data availability

All data and materials can be accessed by contacting the corresponding author.

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References

1. Seminati, E. & Minetti, A. E. Overuse in volleyball training/practice: A review on shoulder and spine-related injuries. *Eur. J. Sport Sci.* **13**, 732–743 (2013).
2. Aagaard, H., Scavenius, M. & Jørgensen, U. An epidemiological analysis of the injury pattern in indoor and in beach volleyball. *Int. J. Sports Med.* **18**, 217–221 (1997).
3. Briner, W. W. & Kacmar, L. Common injuries in volleyball. *Sports Med.* **24**, 65–71 (1997).
4. Dvorak, J. Risk factors and incidence of injuries in football players. *Am. J. Sports Med.* **28**, S1–S74 (2000).
5. Garcia, A. & Redler, L. H. Descriptive epidemiology of injuries sustained in national collegiate athletic association men's and women's lacrosse, 2004–2005 through 2013–2014 seasons. *HSS J.* ® **20**, 288–297 (2023).
6. Keller, R. A., De Giacomo, A. F., Neumann, J. A., Limpisvasti, O. & Tibone, J. E. Glenohumeral internal rotation deficit and risk of upper extremity injury in overhead athletes: A meta-analysis and systematic review. *Sports Health* **10**, 125–132 (2018).
7. Kilic, O., Maas, M., Verhagen, E., Zwerver, J. & Gouttebarge, V. Incidence, aetiology and prevention of musculoskeletal injuries in volleyball: A systematic review of the literature. *Eur. J. Sport Sci.* **17**, 765–793 (2017).
8. Bishop, C., Turner, A. & Read, P. Effects of inter-limb asymmetries on physical and sports performance: A systematic review. *J. Sports Sci.* **36**, 1135–1144 (2018).
9. Croisier, J.-L., Ganteaume, S., Binet, J., Genty, M. & Ferret, J.-M. Strength imbalances and prevention of hamstring injury in professional soccer players: A prospective study. *Am. J. Sports Med.* **36**, 1469–1475 (2008).
10. Mokha, M., Sprague, P. A. & Gatens, D. R. Predicting musculoskeletal injury in national collegiate athletic association division II athletes from asymmetries and individual-test versus composite functional movement screen scores. *J. Athl. Train.* **51**, 276–282 (2016).
11. Mattes, K., Wollesen, B. & Manzer, S. Asymmetries of maximum trunk, hand, and leg strength in comparison to volleyball and fitness athletes. *J. Strength Cond. Res.* **32**, 57–65 (2018).
12. Menzel, H.-J. et al. Analysis of lower limb asymmetries by isokinetic and vertical jump tests in soccer players. *J. Strength Cond. Res.* **27**, 1370 (2013).
13. Wagner, H. et al. Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scand. J. Med. Sci. Sports* **24**, 345–354 (2014).
14. Leporace, G. et al. Ativação muscular do quadril e do joelho em duas aterrissagens realizadas por atletas do sexo masculino. *Revista Brasileira de Medicina do Esporte* **17**, 324–328 (2011).
15. Hernández-Hernández, E., Montalvo-Espinosa, A. & García-de-Alcaraz, A. A time-motion analysis of the cross-over step block technique in volleyball: Non-linear and asymmetric performances. *Symmetry* **12**, 1027 (2020).
16. Schons, P. et al. The relationship between strength asymmetries and jumping performance in professional volleyball players. *Sports Biomech.* **18**, 515–526 (2018).
17. Fort-Vanmeerhaeghe, A., Gual, G., Romero-Rodriguez, D. & Unnitha, V. Lower limb neuromuscular asymmetry in volleyball and basketball players. *J. Hum. Kinet.* **50**, 135–143 (2016).
18. Stephens, T. M. 2nd., Lawson, B. R. & Reiser, R. F. 2nd. Bilateral asymmetries in max effort single-leg vertical jumps. *Biomed. Sci. Instrum.* **41**, 317–322 (2005).
19. Bishop, C. et al. Interlimb asymmetries: The need for an individual approach to data analysis. *J. Strength Cond. Res.* **35**, 695–701 (2021).
20. Smith, C. A., Chimera, N. J. & Warren, M. Association of y balance test reach asymmetry and injury in division I athletes. *Med. Sci. Sports Exerc.* **47**, 136–141 (2015).
21. Brumitt, J., Nelson, K., Duey, D., Jeppson, M. & Hammer, L. Preseason Y Balance Test Scores are not associated with noncontact time-loss lower quadrant injury in male collegiate basketball players. *Sports* **7**, 4 (2018).
22. Markovic, G., Šarabon, N., Pausic, J. & Hadžić, V. Adductor muscles strength and strength asymmetry as risk factors for groin injuries among professional soccer players: A prospective study. *Int. J. Environ. Res. Public Health* **17**, 4946 (2020).
23. Warren, M., Lininger, M. R., Smith, C. A., Copp, A. J. & Chimera, N. J. Association of functional screening tests and noncontact injuries in Division I women student-athletes. *J Strength Cond. Res.* **34**, 2302–2311 (2020).
24. Plisky, P. J., Rauh, M. J., Kaminski, T. W. & Underwood, F. B. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J. Orthop. Sports Phys. Ther.* **36**, 911–919 (2006).
25. Gonell, A. C., Romero, J. A. P. & Soler, L. M. Relationship between the Y balance test scores and soft tissue injury incidence in a soccer team. *Int. J. Sports Phys. Ther.* **10**, 955 (2015).
26. Hartley, E. M., Hoch, M. C. & Boling, M. C. Y-balance test performance and BMI are associated with ankle sprain injury in collegiate male athletes. *J. Sci. Med. Sport* **21**, 676–680 (2018).
27. Hadzic, V., Sattler, T., Veselko, M., Markovic, G. & Dervisevic, E. Strength asymmetry of the shoulders in elite volleyball players. *J. Athl. Train.* **49**, 338–344 (2014).
28. Kozinc, Ž & Šarabon, N. Inter-limb asymmetries in volleyball players: Differences between testing approaches and association with performance. *J. Sports Sci. Med.* **19**, 745 (2020).
29. Ato, M., Lopez, J. J. & Benavente, A. A classification system for research designs in psychology. *Anales de psicología* **29**, 1038–1059 (2013).
30. Bolgla, L. A. Reliability of lower extremity functional performance tests. *J. Orthop. Sports Phys. Ther.* **26**, 138–214 (1997).

31. Baechle, T. R. & Earle, R. W. National strength & conditioning association (US). In *Essentials of Strength Training and Conditioning*, 395–396 (Human Kinetics, 2008).
32. Sands, W. A., Shultz, B. B. & Newman, A. P. Women's gymnastics injuries: A 5-year study. *Am. J. Sports Med.* **21**, 271–276 (1993).
33. Fuller, C. W. et al. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Scand. J. Med. Sci. Sports* **16**, 83–92 (2006).
34. Cuff, S., Loud, K. & O'Riordan, M. A. Overuse injuries in high school athletes. *Clin. Pediatr.* **49**, 731–736 (2010).
35. Brumitt, J., Mattocks, A., Loew, J. & Lentz, P. Preseason functional performance test measures are associated with injury in female college volleyball players. *J. Sport Rehabil.* **29**, 320–325 (2020).
36. Read, P. J., Oliver, J. L., De Ste Croix, M., Myer, G. D. & Lloyd, R. S. A prospective investigation to evaluate risk factors for lower extremity injury risk in male youth soccer players. *Scand. J. Med. Sci. Sports* **28**, 1244–1251 (2018).
37. Iglesias-Caamaño, M., Carballo-López, J., Álvarez-Yates, T., Cuba-Dorado, A. & García-García, O. Intrasession reliability of the tests to determine lateral asymmetry and performance in volleyball players. *Symmetry* **10**, 416 (2018).
38. Xie, H., Hongsaenyatham, P. & Rittisom, S. Reducing limb asymmetry in females collegiate basketball: A randomized trial. *Int. J. Soc. Anthropol. Sci. Rev.* **4**, 417–426 (2024).
39. Paterno, M. V. et al. Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am. J. Sports Med.* **38**, 1968–1978 (2010).
40. Kozinc, Ž, Žitnik, J., Smajla, D. & Šarabon, N. The difference between squat jump and countermovement jump in 770 male and female participants from different sports. *Eur. J. Sport Sci.* **22**, 985–993 (2022).
41. Pain, M. T. Considerations for single and double leg drop jumps: Bilateral deficit, standardizing drop height, and equalizing training load. *J. Appl. Biomech.* **30**, 722–727 (2014).
42. Hughes, J. D., Massiah, R. G. & Clarke, R. D. The potentiating effect of an accentuated eccentric load on countermovement jump performance. *J. Strength Cond. Res.* **30**, 3450–3455 (2016).
43. Nimphius, S., Callaghan, S. J., Spiteri, T. & Lockie, R. G. 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).
44. Miller, M. G., Herniman, J. J., Ricard, M. D., Cheatham, C. C. & Michael, T. J. The effects of a 6-week plyometric training program on agility. *J. Sports Sci. Med.* **5**, 459 (2006).
45. Dos SDos'antos, T., Thomas, C., Jones, P. A. & Comfort, P. Assessing asymmetries in change of direction speed performance: Application of change of direction deficit. *J. Strength Cond. Res.* **33**, 2953–2961 (2019).
46. Impellizzeri, F. M., Rampinini, E., Maffiuletti, N. & Marcora, S. M. A vertical jump force test for assessing bilateral strength asymmetry in athletes. *Med. Sci. Sports Exerc.* **39**, 2044 (2007).
47. Sattler, T., Sekulic, D., Esco, M. R., Mahmutovic, I. & Hadzic, V. Analysis of the association between isokinetic knee strength with offensive and defensive jumping capacity in high-level female volleyball athletes. *J. Sci. Med. Sport* **18**, 613–618 (2015).
48. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences* (Routledge, 2013).
49. Cheung, R., Smith, A. & Wong, D. H: Q ratios and bilateral leg strength in college field and court sports players. *J. Hum. Kinet.* **33**, 63–71 (2012).
50. Hadzic, V., Sattler, T., Markovic, G., Veselko, M. & Dervisevic, E. The isokinetic strength profile of quadriceps and hamstrings in elite volleyball players. *Isokinet. Exerc. Sci.* **18**, 31–37 (2010).
51. Chaitidou, V. & Panoutsakopoulos, V. Long jump performance is not related to inter-limb asymmetry in force application in isometric and vertical jump tests. *Biomechanics* **3**, 389–400 (2023).
52. Lockie, R. G. et al. Certain actions from the Functional Movement Screen do not provide an indication of dynamic stability. *J. Hum. Kinet.* **47**, 19 (2015).
53. Bishop, C. et al. Drop jump asymmetry is associated with reduced sprint and change-of-direction speed performance in adult female soccer players. *Sports* **7**, 29 (2019).
54. Hart, N. H., Spiteri, T., Lockie, R. G., Nimphius, S. & Newton, R. U. Detecting deficits in change of direction performance using the preplanned multidirectional Australian football league agility test. *J. Strength Cond. Res.* **28**, 3552–3556 (2014).
55. Madruga-Parera, M. et al. Interlimb asymmetries in youth tennis players: Relationships with performance. *J. Strength Cond. Res.* **34**, 2815–2823 (2020).
56. Hamilton, R. T., Shultz, S. J., Schmitz, R. J. & Perrin, D. H. Triple-hop distance as a valid predictor of lower limb strength and power. *J. Athl. Train.* **43**, 144–151 (2008).
57. Meylan, C. M., Nosaka, K., Green, J. & Cronin, J. B. Temporal and kinetic analysis of unilateral jumping in the vertical, horizontal, and lateral directions. *J. Sports Sci.* **28**, 545–554 (2010).
58. Parkinson, A. O., Apps, C. L., Morris, J. G., Barnett, C. T. & Lewis, M. G. The calculation, thresholds and reporting of inter-limb strength asymmetry: A systematic review. *J. Sports Sci. Med.* **20**, 594 (2021).
59. Tillman, M. D., Hass, C. J., Brunt, D. & Bennett, G. R. Jumping and landing techniques in elite women's volleyball. *J. Sports Sci. Med.* **3**, 30 (2004).
60. Ireland, M. L. Anterior cruciate ligament injury in female athletes: Epidemiology. *J. Athl. Train.* **34**, 150 (1999).
61. Schafle, M. D. Common injuries in volleyball: Treatment, prevention and rehabilitation. *Sports Med.* **16**, 126–129 (1993).
62. Zhang, S.-N., Bates, B. T. & Dufek, J. S. Contributions of lower extremity joints to energy dissipation during landings. *Med. Sci. Sports Exerc.* **32**, 812–819 (2000).
63. Fort-Vanmeerhaeghe, A., Milà-Villarroel, R., Pujol-Marzo, M., Arboix-Alió, J. & Bishop, C. Higher vertical jumping asymmetries and lower physical performance are indicators of increased injury incidence in youth team-sport athletes. *J. Strength Cond. Res.* **36**, 2204–2211 (2022).
64. Guan, Y. Research on the collaborative path of integrating ideological and political content into college physical education teaching. *Curric. Teach. Methodol.* **6**, 130–134 (2023).
65. Boden, B. P., Dean, G. S., Feagin, J. A. & Garrett, W. E. Mechanisms of anterior cruciate ligament injury. *Orthopedics* **23**, 573–578 (2000).
66. Cochrane, J. L., Lloyd, D. G., Buttfield, A., Seward, H. & McGivern, J. Characteristics of anterior cruciate ligament injuries in Australian football. *J. Sci. Med. Sport* **10**, 96–104 (2007).
67. Brophy, R. H., Stepan, J. G., Silvers, H. J. & Mandelbaum, B. R. Defending puts the anterior cruciate ligament at risk during soccer: A gender-based analysis. *Sports Health* **7**, 244–249 (2015).
68. Jones, P. A., Herrington, L. C. & Graham-Smith, P. Technique determinants of knee joint loads during cutting in female soccer players. *Hum. Mov. Sci.* **42**, 203–211 (2015).
69. Kristianslund, E., Faul, O., Bahr, R., Myklebust, G. & Krosshaug, T. Sidestep cutting technique and knee abduction loading: Implications for ACL prevention exercises. *Br. J. Sports Med.* **48**, 779–783 (2014).
70. Dai, B. et al. The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. *Am. J. Sports Med.* **43**, 466–474 (2015).
71. Dempsey, A. R. et al. The effect of technique change on knee loads during sidestep cutting. *Med. Sci. Sports Exerc.* **39**, 1765–1773 (2007).
72. Jones, P. A. & Bampouras, T. M. A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. *J. Strength Cond. Res.* **24**, 1553–1558 (2010).
73. Sell, T. C. et al. Predictors of proximal tibia anterior shear force during a vertical stop-jump. *J. Orthop. Res.* **25**, 1589–1597 (2007).

74. Eagle, S. R. et al. Bilateral quadriceps strength asymmetry is associated with previous knee injury in military special tactics operators. *J. Strength Cond. Res.* **33**, 89–94 (2019).
75. Koźlenia, D., Struzik, A. & Domaradzki, J. Force, power, and morphology asymmetries as injury risk factors in physically active men and women. *Symmetry* **14**, 787 (2022).

Author contributions

P.W. mostly wrote the first draft. Z.K. is mainly responsible for the revision and formatting of paper submissions. Z.M. is primarily responsible for methodological guidance and supervision.

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Declarations

Competing interests

The authors declare no competing interests.

Ethics approval and consent to participate

The study followed the guidelines of the Helsinki Declaration. All participants signed informed consent forms before participating in the research protocol. The Ethics and Ethics Committee of the Capital University of Physical Education and Sports has approved this study.

Consent for publication

All authors gave consent for the publication. Informed consent to publish was obtained from the subjects and their legal guardians. All photos are published with permission for open publication and with the subject's or their parent's permission. Association Between Pre-Season Lower Limb Interlimb Asymmetry and Non-Contact Lower Limb Injuries in Elite Male Volleyball Players is licensed under Attribution 4.0 International. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

Additional information

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