Laterality of Dynamic and Static Balance Abilities in Volleyball Players (Postprint)

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Date: 2025-11-01T00:00:00+00:00

Abstract

Objective: To analyze the biomechanical characteristics of single-leg standing and single-leg landing in volleyball players' dominant and non-dominant legs, explore the differences in dynamic and static balance abilities between the dominant and non-dominant legs, and provide a theoretical direction for designing postural control training programs for volleyball players. Methods: Twenty volleyball players were selected to perform 30-second eyes-open and eyes-closed single-leg standing tests and 40-cm box single-leg landing stability tests on both dominant and non-dominant legs. Differences in static standing center of pressure (COP) parameters, joint angles at ground contact and joint range of motion, stability indices, loading rate, peak ground reaction force, and time to peak ground reaction force were compared. Results: (1) Static balance ability: No significant differences were found in COP indices between non-dominant and dominant legs during eyes-open single-leg standing ($P>0.05$). During eyes-closed single-leg standing, the dominant leg showed significant differences compared to the non-dominant leg in maximum anterior-posterior displacement distance of COP and average velocity of COP in the anterior-posterior direction ($P<0.05$). (2) Dynamic balance ability: Significant differences were observed between non-dominant and dominant legs in anterior-posterior stability index, medial-lateral stability index, vertical stability index, and dynamic stabilization time calculated from GRF during single-leg landing ($P<0.05$). During the landing buffering process, the non-dominant leg showed significant differences in knee and ankle range of motion compared to the dominant leg ($P<0.05$). Significant differences in loading rate were found between dominant and non-dominant legs during single-leg landing ($P<0.05$), and the loading rate symmetry index indicated laterality. Conclusion: Laterality exists in balance ability between dominant and non-dominant legs in volleyball players. Regarding static balance ability, under eyes-open conditions, static balance ability was similar between both lower limbs, while under eyes-closed conditions, the dominant leg demonstrated better static balance ability in the sagittal plane, with greater visual compensation in the non-dominant side. Regarding dynamic balance ability, the non-dominant leg outperformed the dominant leg, with laterality existing between both lower limbs. In volleyball players' physical training programs, focused attention should be given to strengthening eyes-closed static balance ability of the non-dominant leg and dynamic postural control training of the dominant leg, thereby reducing landing injury risk and enhancing athletic performance in single-leg support and force-generation movements.

Full Text

Vol. 42 No. 5
Oct. 2025
Chinese Journal of Applied Mechanics DOI: 10.11776/j.issn.1000-4939.2025.05.021

Study of Lateralization in Dynamic and Static Balance Abilities of Volleyball Players

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Abstract: Objective To analyze the biomechanical characteristics of single-leg stance and single-leg landing in the dominant and non-dominant legs of volleyball players and explore the differences in static and dynamic balance abilities between the two legs so as to provide theoretical guidance for the design of posture control training programs for volleyball players. Methods Twenty volleyball players were selected to perform 30-second single-leg stance tests (with eyes open and closed) and 40 cm box jump single-leg landing stability tests using both the dominant and non-dominant legs. The study compared the differences in center of pressure (COP) parameters during static stance, joint angles and range of motion at the moment of ground contact during landing, stability index, loading rate, peak ground reaction force (GRF), and the time to reach peak ground reaction force. Results (1) Static balance ability: No significant differences were observed in COP parameters between the dominant and non-dominant legs during single-leg stance with the eyes open ($P > 0.05$). However, during single-leg stance with the eyes closed, the maximum displacement and average velocity of COP in the anterior-posterior direction of the dominant leg showed significant differences compared to the non-dominant leg ($P < 0.05$). (2) Dynamic balance ability: Significant differences were found between the dominant and non-dominant legs in the anterior-posterior stability index, lateral stability index, vertical stability index, and dynamic stability time calculated from GRF during single-leg landing (P < 0.05). During the landing cushioning phase, significant differences in knee and ankle joint mobility were observed between the non-dominant and dominant legs (P < 0.05). Additionally, the loading rate during single-leg landing showed significant differences between the two legs (P < 0.05), and the loading rate symmetry index indicated lateralization. Conclusion There is lateralization in the balance abilities between the dominant and non-dominant legs of volleyball players. In terms of static balance ability, the two legs exhibit similar performance under eyes-open conditions. However, under eyes-closed conditions, the dominant leg demonstrates better static balance in the sagittal plane, while the non-dominant leg relies more on visual compensation. In terms of dynamic balance ability, the non-dominant leg performs better than the dominant leg, indicating lateralization between the two legs. In designing physical training programs for volleyball players, special attention should be paid to enhancing the static balance ability of the non-dominant leg under eyes-closed conditions and improving the dynamic posture control of the dominant leg. This will help reduce the risk of landing injuries and improve the performance of single-leg support and force application movements.

Key words: volleyball player; static and dynamic balance ability; lateralization; sports-induced injury

However, the lateralization effect of balance ability in volleyball players has not received adequate attention, and few studies have reported whether differences exist between the dominant and non-dominant legs. In various ball sports involving jumping and landing, single-leg balance ability is crucial for the development of motor skills [1-2], especially for high-center-of-gravity players like volleyball athletes [3]. Superior single-leg balance ability helps volleyball players maintain body stability and precise control when executing technical movements such as single-leg jumps, side-support jumps, and step-close spikes [4]. Meanwhile, good dynamic single-leg balance ability can reduce lower extremity injuries in volleyball players during landing [5]. However, current research on balance ability typically assumes lower limb symmetry, observing only one side' s data to evaluate balance ability, or selecting only the dominant leg' s stability as the evaluation basis [6-7], which does not align with actual sports performance. In competitions, athletes often use one leg to perform complex and powerful movements while the other leg provides support and balance, a phenomenon known as lateralization [8]. Lateralization was first proposed by neurophysiologists BROWN et al. [9] and has been proven to be a factor influencing injury incidence [10-11]. This functional differentiation and postural difference between lower limbs significantly affects individual athletic performance.

Based on this, this study compared and analyzed the kinematics, dynamics, loading rate, stability index, and other indicators between the dominant and non-dominant legs of volleyball players during single-leg stance and single-leg landing. By evaluating the differences between both lower limbs in single-leg dynamic and static balance tasks, this study aims to provide reference data for improving athletic performance and injury prevention.

1. Research Methods

1.1 Participants

This study recruited volleyball players in Tianjin from May to August 2024. Sample size was estimated using G*Power 3.1 software, selecting a large effect size of 0.6, significance level of 0.05, and test power of 0.8 [12], resulting in a total sample size of 13. Considering potential participant dropout, 20 subjects were ultimately selected, including 10 first-level and 10 second-level athletes. The athletes had no lower extremity injuries in the past 6 months and no neurological or chronic non-communicable diseases. This study was approved by the Ethics Committee of Tianjin University of Sport (TJUS2023-050).

1.2 Experimental Protocol

1.2.1 Static Balance Test A three-dimensional force measurement system was used to collect data during 30-second single-leg stance tests with eyes open and closed, with a sampling frequency of 1,000 Hz. Bioware software was used to extract the center of pressure (COP) data, which was low-pass filtered with a cutoff frequency of 10 Hz. COP displacement was used to quantify body sway and assess static balance. During testing, subjects were required to focus on a fixed point 4 m in front of the body, place hands on the waist, keep the non-test leg' s calf perpendicular to the test leg and thigh parallel to the test leg, and stand on one leg for 30 s. During this process, the test leg was not allowed to move. Both legs were tested alternately for 3 trials each, with 1-minute rest intervals [13]. The starting leg for each subject was randomly determined, see Figure 1

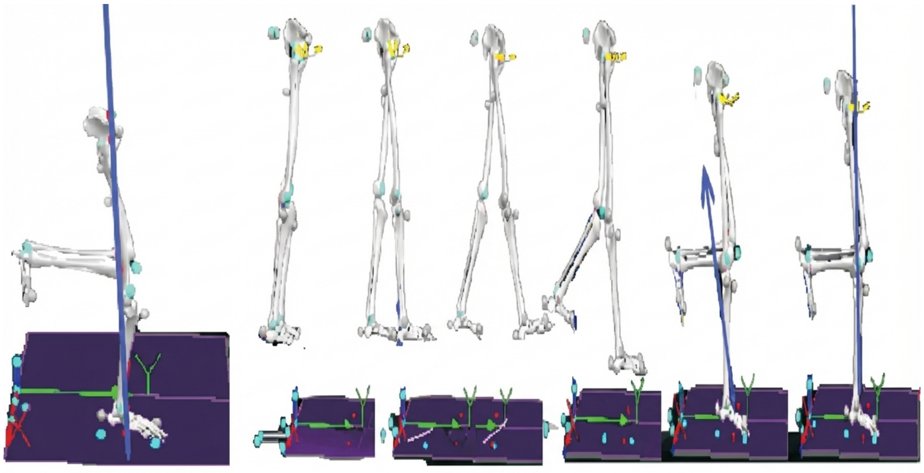

(a) Single-leg Stance
(b) Single-leg Drop Landing

Figure 1: Figure 1

(a).

1.2.2 Dynamic Balance Test A three-dimensional force measurement system and three-dimensional motion capture system were used to collect data during single-leg landing from a 40 cm box, with sampling frequencies of 1,000 Hz and 200 Hz, respectively. Athletes stood on the box as required, lifted the test leg off the box surface and placed it at the box edge, gradually shifted the body center of gravity forward. When the projection of the body center of gravity left the box, the body dropped in free-fall and then landed on the force plate center in a single-leg posture with no vertical initial velocity at the moment of landing [14]. After landing, the test leg naturally flexed at the knee for cushioning and maintained the cushioning posture, while the non-landing leg naturally bent backward to 90°.

Test failure criteria [15]: The support leg moved within 10 s after landing; Abnormal forward trunk lean or sway occurred after landing; The non-landing leg contacted the landing leg or box; Obvious adjustment movements occurred after landing (e.g., sudden stop or rapid swing). The landing criteria were the same for dominant and non-dominant legs. Tests were performed alternately on both legs, with 3 trials per leg and 1-minute intervals, see Figure 1(b).

The 40 cm box height selected in this study referenced the box heights used in dynamic single-leg landing balance ability lateralization tests for athletes in other sports, such as tennis [13], aerobics [16], and soccer [17]. This height selection facilitates cross-sport comparative analysis. Meanwhile, studies have shown that volleyball players' jumping height in competition ranges from 35-50 cm [18]. Therefore, selecting 40 cm as the box height both matches volleyball players' actual jumping height and accurately simulates athletes' competitive states, providing appropriate experimental conditions for dynamic balance ability testing.

This study used the commonly employed kicking method to determine leg dominance. Before testing, subjects were asked to kick a ball with maximum effort 3 times with each leg; the leg that kicked the farthest was defined as the dominant leg [13,19].

1.3 Data Processing

1.3.1 Static Balance Ability The x-axis and y-axis values exported from Bioware software represent COP displacement in the medial-lateral (ML) and anterior-posterior (AP) directions, respectively. The COP data were calculated with the following main indicators: maximum displacement of COP in AP direction (Ky), maximum displacement of COP in ML direction (Kx), average velocity of COP in AP direction (Kv), average velocity of COP in ML direction (Ku), and 95% COP sway area (Kp) [20]. The calculation formulas are:

$$i = 1\frac{y_{i+1} - y_i}{t_{i+1} - t_i}\frac{x_{i+1} - x_i}{t_{i+1} - t_i}$$

$$Ky = y_a - y_b$$

$$Kx = x_a - x_b$$

$$Kp = (x_a - x_b) \times (y_a - y_b) \times \pi$$

Where: Ky and Kx represent AP and ML COP range; ya and yb are the maximum and minimum AP values; xa and xb are the maximum and minimum ML values; Kv and Ku represent the average velocity of COP in AP and ML directions, calculated by dividing the position difference between two adjacent time points by the time difference, taking the absolute value, and averaging across all N points; Kp is the 95% ellipse area.

Figure 2 [FIGURE:2] shows the COP trajectory of one athlete during testing. The figure visually demonstrates that the pressure center point continuously changes during balance maintenance, with continuous fluctuations in both AP and ML directions.

1.3.2 Dynamic Balance Ability

1) Joint angle at ground contact: The angle of the lower limb three joints in three-dimensional planes at the moment of landing. Landing moment: when vertical ground reaction force (VGRF) first exceeds 10 N.
2) Joint range of motion: The range of motion of the lower limb three joints from landing moment to 10 s after landing.
3) Stability index: The stability index was calculated using GRF during the first 3 s after initial ground contact (VGRF $\geq$ 10 N) [9,21], including anterior-posterior stability index (Ks), medial-lateral stability index (Kt), and vertical stability index (Ki).

$$Ks = \sqrt{\frac{\sum(0 - Fa)^2}{N}}$$

$$Kt = \sqrt{\frac{\sum(0 - Fm)^2}{N}}$$

$$Ki = \sqrt{\frac{\sum(W - Fv)^2}{N}}$$

Where Ks is the anterior-posterior stability index; Kt is the medial-lateral stability index; Ki is the vertical stability index; Fa, Fm, and Fv represent ground reaction forces in anterior-posterior, medial-lateral, and vertical directions, respectively; N is the number of sampling points; W is body mass.

Figure 3

shows the ground reaction force variation curve of one athlete during single-leg landing. The figure shows that all three directional forces exhibit significant fluctuations with landing impact, reflecting the lower limb’ s cushioning and stability adjustment process.

Note: Positive values in the anterior-posterior direction represent forward GRF direction, negative values represent backward; positive values in the medial-lateral direction represent rightward GRF direction, negative values represent leftward; positive values in the vertical direction represent upward GRF direction.

4) Peak vertical ground reaction force and time to reach peak vertical ground reaction force. The peak vertical ground reaction force was normalized and expressed as a percentage of body mass [10].

5) Loading rate (LR)

$$Kr = \frac{Fp}{tp}$$

Where: Kr is the loading rate; Fp is the peak vertical ground reaction force; tp is the time required to reach peak vertical ground reaction force.

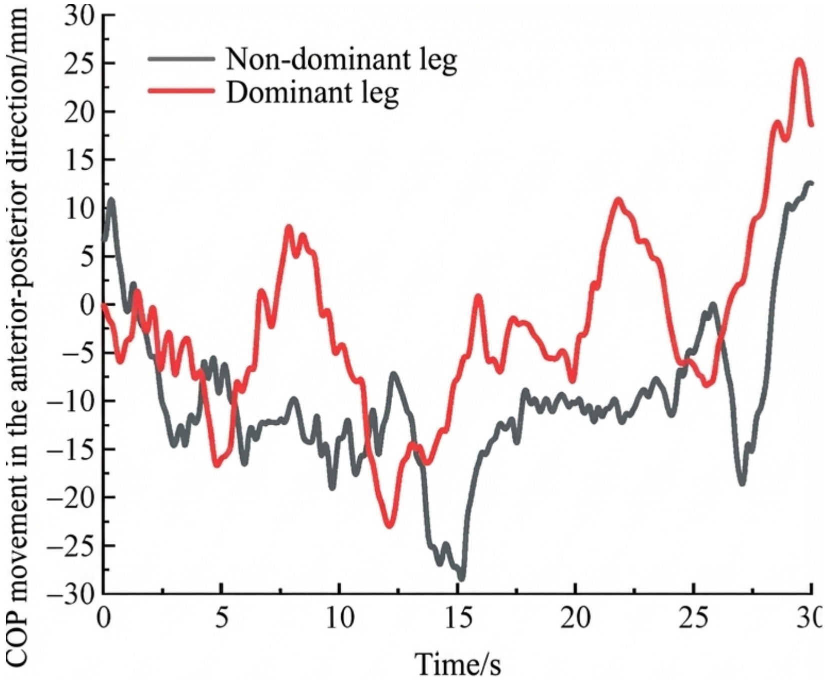
6) Absolute symmetry index (ASI)

$$Ka = \frac{(|Ld - Ln|)}{0.5 \times (Ld + Ln)} \times 100\%$$

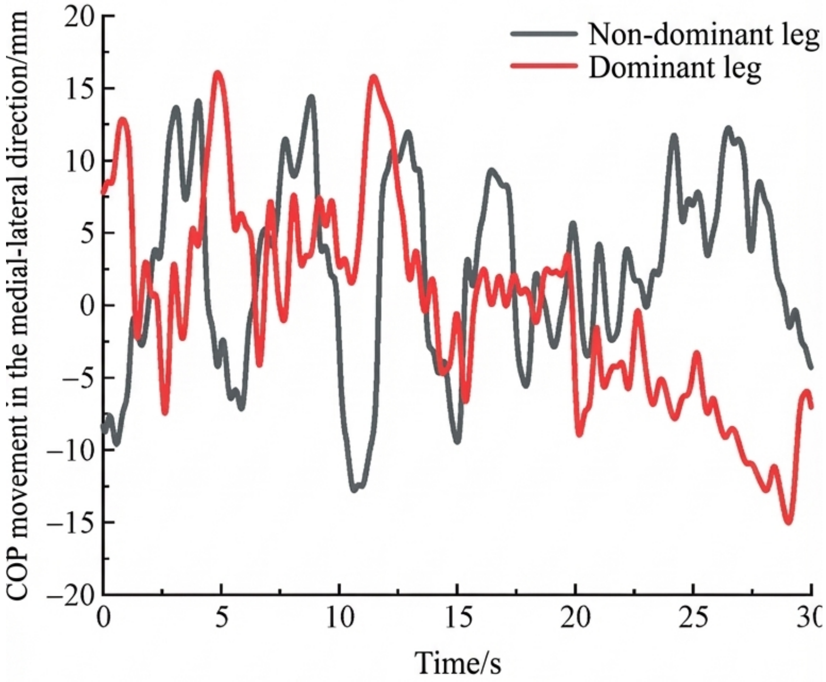
Where: Ld and Ln represent the peak vertical ground reaction force of the dominant and non-dominant legs, respectively; Ka is the symmetry index. When Ka $= 0$, it indicates bilateral symmetry; when $0 <$ Ka $\leq 10\%$, it indicates relatively symmetric lower limbs; when Ka $> 10\%$, it indicates lower limb asymmetry.

1.4 Statistical Analysis

Data were analyzed using SPSS 26.0 statistical software. The Shapiro-Wilk test verified data normality. For normally distributed data, paired t-tests were used for analysis; for non-normally distributed data, non-parametric tests were used. The significance level was set at $\alpha = 0.05$.



(a) Anterior-posterior direction



(b) Medial-lateral direction

Figure 2: Figure 3

2. Results

2.1 Static Balance Test Results

In static balance testing, no significant differences were found between dominant and non-dominant legs in Ky, Kx, Kv, Ku, or Kp indicators ($P > 0.05$), see Table 1 .

2.2 Dynamic Balance Test Results

2.2.1 Kinematic Characteristics of Single-Leg Landing No significant differences were found in joint angles at ground contact between non-dominant and dominant legs, see Table 2 . Regarding joint range of motion, the knee and ankle joint mobility of the non-dominant leg in the sagittal plane were significantly greater than those of the dominant leg; in the frontal plane, the knee joint mobility of the dominant leg was significantly greater than that of the non-dominant leg, see Figure 4 [FIGURE:4].

2.2.2 Dynamic Characteristics of Single-Leg Landing As shown in Table 3 , no significant differences were found in Fp between non-dominant and dominant legs; tp and Ka showed significant differences, see Table 3. The Ki value was 18.31 ± 6.45, greater than 10%.

2.2.3 Stability Indices of Single-Leg Landing In dynamic balance testing, the Ks, Kt, and Ki of the non-dominant leg were all significantly smaller than those of the dominant leg, see Figure 5 [FIGURE:5].

3. Discussion and Analysis

In this study, leg dominance was determined based on the leg commonly used for kicking or the leg that kicked farther. This method has been used in multiple sports, including soccer [17], tennis [13], freestyle skiing [7], and competitive aerobics [16], rather than being based solely on the specific sport the athlete participates in. Therefore, this study also used the same method to determine volleyball players' dominant leg. The study found that in static balance testing, the balance performance of dominant and non-dominant legs was the same with eyes open, but the dominant leg showed significantly better balance with eyes closed. This indicates that vision plays an important role in balance control [20]. In dynamic balance testing, the non-dominant leg showed stronger stability and recovery ability in all directions, indicating better biomechanical adaptation and neuromuscular control capabilities during landing, particularly in high-intensity movements.

3.1 Static Balance Ability

In volleyball competitions, good static balance ability helps athletes transition smoothly from static to dynamic states. The study shows that different performances with eyes open and closed highlight the critical role of vision in maintaining balance. KOZINC [13] demonstrated that balance control involves multiple systems: the neuromuscular system controls body posture; the vestibular and proprioceptive systems provide body position sense; and the visual system provides positional information [22]. Among these systems, vision is crucial for postural control. When other senses are compromised, visual compensation plays an important role. In eyes-closed testing, the Kv and Ku data of dominant and non-dominant legs indicate that both legs have different postural control capabilities in the anterior-posterior direction. Previous studies have proposed that when body balance is disturbed, the dynamic inhibition system composed of muscles and proprioception can help maintain stability [23]. Muscle strength studies show that dominant leg muscle strength is typically greater than non-dominant leg [17]. Volleyball players frequently move and jump in the anterior-posterior direction during competition and training, so the dominant leg bears more load, promoting further muscle development and thereby improving balance control ability. In daily training, athletes should focus on strengthening the non-dominant leg to compensate for the impact of missing visual information on balance, thereby improving stability and reaction capability in complex competition environments.

3.2 Dynamic Balance Ability

In volleyball, landing after jumping requires greater lower extremity stability, especially after spiking or blocking when athletes need to quickly recover balance and cushion impact. Single-leg landing is a common method to simulate landing in volleyball and is frequently used in laboratory testing due to its high complexity [24]. The control of center of gravity after landing directly reflects injury risk. Ks, Kt, and Ki measure the body' s ability to decelerate the center of gravity in each direction [23]. The data show that the non-dominant leg has better stability than the dominant leg in all directions, demonstrating its biomechanical adaptation ability during landing, particularly in high-intensity movements where the non-dominant leg can more effectively control landing through training and adaptation. Meanwhile, ZAHRADNIK et al. [25] also found that during unilateral jump landing, the dominant leg showed higher knee and ankle oscillation frequencies, demonstrating obvious lateralization.

Further analysis shows that in the initial landing phase, no significant differences exist between dominant and non-dominant legs in three-dimensional directions, indicating that athletes adopt similar landing strategies at this stage. Lateralization mainly appears in the subsequent cushioning phase. By comparing joint range of motion in the sagittal plane, the non-dominant leg showed greater knee and ankle mobility during cushioning. Studies have indicated that "soft landing" [16] is an effective strategy to reduce sports injury risk, and the non-dominant leg has lower injury risk during landing. Kr is an important indicator for evaluating landing cushioning patterns, measuring athletes' ability to absorb ground reaction forces [17]. The study found that Kr and Ka of the dominant leg indicate that both lower limbs have not evenly borne impact forces during long-term training. Kr is closely related to Kp and tp. Although Fp showed no significant difference between legs, tp of the dominant leg was significantly smaller than that of the non-dominant leg, indicating that the dominant leg responds faster to landing impact. Based on kinematic data results, it is speculated that dominant and non-dominant legs adopt different strategies during landing. The dominant leg mainly relies on rigid tissues (such as ligaments and joints) for cushioning, which can quickly complete landing but may also cause over-impact-related injuries such as ligament damage. In contrast, the non-dominant leg shares impact forces in a more coordinated manner, particularly through the muscle groups of the hip and knee joints. Studies have shown that differences in lower extremity joint cushioning ability and balance ability reflect differences in neuromuscular control [26-27]. The nervous system helps athletes effectively absorb impact and maintain balance by regulating muscle activity [28]. During non-dominant leg landing, the nervous system distributes ground reaction forces and reduces joint and ligament pressure by optimizing control strategies and coordinating related muscle groups. In contrast, the neuromuscular control of the dominant leg may be less flexible, especially when facing greater impact.

Additionally, kinematic indicator differences are not only evident in the sagittal plane but also in the frontal plane. The study found that the dominant leg showed significantly greater knee varus/valgus angles than the non-dominant leg during landing. Knee instability is a risk factor for anterior cruciate ligament injury [11,29], particularly when athletes need to quickly adapt to complex movement tasks. Facing higher Kr, the dominant leg failed to effectively cushion through ankle, knee, and hip in the sagittal plane, instead over-compensating by increasing joint range of motion in the frontal plane [30]. This compensation mechanism may cause excessive stretching of ligaments such as the ACL, thereby increasing injury risk. Based on this study' s results, it can be speculated that the higher stability of the non-dominant leg may be closely related to its more efficient muscle synergy patterns and neural control strategies. By activating earlier and working more coordinately, the non-dominant leg can better share impact forces and reduce landing load. Future electromyography studies [31] will help more intuitively understand how the non-dominant leg coordinates muscle groups to reduce impact load and provide stronger data support for lateralization and injury prevention in volleyball players.

Limitations of this study: The test data lack surface electromyography data, preventing a more intuitive and accurate understanding of the lateralization of volleyball players' dynamic and static balance abilities from a neuromuscular control perspective; In dynamic balance testing, this study only investigated dynamic stability related to forward jump landing. Although this may be the most common situation in actual competition, it is not the only single-leg landing method. Future studies should test multiple jump landing directions, such as lateral and diagonal; Both physical and mental fatigue can affect the performance of dominant and non-dominant legs in dynamic and static balance tasks, thereby affecting lateralization results. This factor should be considered in future studies.

Volleyball players exhibit certain lateralization in dynamic and static balance abilities. In static balance, both legs show similar balance ability with eyes open; however, with eyes closed, the dominant leg demonstrates better static balance in the sagittal plane, while the non-dominant leg relies more on visual compensation. In dynamic balance, the non-dominant leg performs better than the dominant leg, showing obvious lateralization. Therefore, future training programs should focus on improving the non-dominant leg' s eyes-closed static balance ability and the dominant leg' s dynamic balance ability, thereby improving athletic performance and reducing injury risk.

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