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ORIGINAL RESEARCH

Position-specific neuromuscular activation and biomechanical characterization of the snap jump in elite male volleyball players: a comparative study of outside and opposite hitters

Chen Chen[1,2,†], Jiali Zhong[2,3,†], Zining Zhu[1,†], Ying Wang[4], Kunyi Huang[5,*], Han Yuan[6,*], Mingli Deng[7], Yuwen ShangGuan[1,*]

[1] Physical Education Department, Kunsan National University, 541150 Gunsan, Republic of Korea
[2] Physical Education Department, Yanshan University, 06000 Qinhuangdao, Hebei, China
[3] Physical Education Department, Sanya University East Campus, 572000 Sanya, Hainan, China
[4] Faculty of Education, Woosuk University, 54896 Jeonju, Republic of Korea
[5] Department of Health and Physical Education, The Education University of Hong Kong, 999077 Hong Kong
[6] Department of Physical Education, Graduate School, Kyungpook National University, 41566 Daegu, Republic of Korea
[7] School of Marxism, Changsha Medical University, 410219 Changsha, Hunan, China

***Correspondence**
980202-5620030@kunsan.ac.kr (Yuwen ShangGuan);
yuanhan202104@163.com (Han Yuan);
kunyihuang88@gmail.com (Kunyi Huang)

† These authors contributed equally.

Abstract

Background: This study aimed to explore the biomechanical and neuromuscular differences in spike jumps between Outside Hitters (OH) and Opposite Hitters (OPP) in volleyball. **Methods**: Twelve male national-level volleyball players (six OHs and six OPPs) performed standardized spike maneuvers aligned with their positional roles. Kinematic data were captured using a Qualisys infrared motion capture system, and muscle activation was assessed using a Delsys wireless surface electromyography (sEMG) system. **Results**: OPPs demonstrated significantly greater right foot landing angle, inter-foot distance and center of mass projection-related distances, indicating a more forward-oriented posture and longer final step. In contrast, OHs exhibited larger shoulder joint line angle and take-off angle, contributing to higher vertical jump performance. Both groups showed asymmetrical force application—right-leg dominance in the braking phase and left-leg dominance in the propulsion phase. Muscle activation patterns were position-specific: OHs relied more on vastus lateralis and gastrocnemius, while OPPs showed greater semitendinosus contribution during propulsion. **Conclusions**: These position-specific neuromechanical patterns reflect distinct tactical demands, suggesting the need for tailored strength and conditioning programs to enhance performance and reduce injury risks in elite volleyball players.

Keywords

Spike jump; Outside hitter; Opposite hitter; Biomechanics; Surface electromyography; Kinematics; Muscle activation

1. Introduction

Volleyball is a highly technical competitive sport, in which spiking, as the most direct and effective means of scoring, plays a decisive role in the victory or defeat of the game [1]. The effectiveness of the spiking technique depends largely on the quality of the spiking jump, which directly affects the height, power and accuracy of the dunking [2]. From a biomechanical point of view, the spike jump process can be divided into two main parts: the approach phase and the take-off phase. The approach phase is intended to generate greater horizontal velocity, while the take-off phase is responsible for efficiently converting this horizontal velocity into vertical velocity [3]. The efficiency of this conversion process directly determines the height of the jump, which is a critical factor influencing the success rate of the spike [4]. Studies have shown that jump height is influenced by a variety of factors, including approach speed, conversion velocity, take-off angle, and knee and ankle angles, *etc.* [5]. In particular, the last step of the three-step approach serves as a key transitional phase for converting horizontal momentum into vertical momentum, and the technical execution during this step has a significant impact on overall take-off performance [6]. Studies have shown that knee joint angular velocity, ankle joint angular velocity, horizontal to vertical velocity conversion ratio, and swing arm amplitude are decisive factors affecting jump height [7].

In modern volleyball, the trend of positional specialization is becoming more and more obvious as the level of competition continues to improve. As two key offensive positions, the Outside Hitter (OH) and the Opposite Hitter (OPP) have significant differences in technical requirements and tactical responsibilities: the OH usually attacks from the left side of the court (No. 4 position), and at the same time undertakes the task of receiving and serving the ball, which requires a quick transition from defense to offense [8]; the OPP mainly attacks from the right side (No. 2 position), not involved in serving or receiving, but faces more complex blocking formations, requiring greater adaptability [9]. It has been shown that there are subtle differences in step rhythm and step length between athletes in these two positions [10]. Additionally, for the back-row offense, which is often executed by OH, the key factors for success include appropriate take-off angle and sufficient horizontal velocity [11]. Compared with front-row spikes, back-row attacks exhibit greater resultant velocity of the center of mass and increased horizontal displacement during the approach jump. Conversely, front-row attacks are characterized by greater initial velocity and higher angular velocities at the upper limb joints [12].

From the perspective of neuromuscular control, the spike jump is a complex, multi-joint coordinated movement. Integral electromyography (iEMG) analysis shows that different muscles play different functions in the various stages of the spike jump: the rectus femoris is mainly responsible for maintaining the balance of the body, while the medial and lateral heads of the gastrocnemius muscles play an important role in stabilizing the aerial posture [13]. It is worth noting that volleyball players often exhibit asymmetric force exertion in both legs, which may lead to higher ground reaction forces or muscle imbalances on one side, thus increasing the risk of injury [14]. Therefore, understanding and optimizing muscle activation patterns has dual implications for improving athletic performance and reducing injury risk.

Recent studies have emphasized that different landing strategies—such as stiff, soft or asymmetrical landings—can significantly influence joint loading and injury susceptibility, particularly in sports involving repetitive jump-landing tasks like volleyball [15]. Asymmetrical neuromuscular activation, especially between dominant and non-dominant legs, has been associated with increased anterior cruciate ligament (ACL) and patellofemoral joint stress [16]. Moreover, tactical differences between OH and OPP may lead to distinct adaptations in landing patterns and neuromuscular strategies. Recent research has advocated for optimizing landing strategies to reduce injury risk through individualized neuromuscular training [17], while time-resolved kinematic analysis has revealed subtle biomechanical distinctions in landing from spike [18]. These findings highlight the need to consider position-specific neuromechanical profiles and their injury implications when evaluating spike jump performance in elite volleyball players.

Despite the widely recognized importance of the spike jump, there is still limited systematic research on the biomechanical properties of the spike jump for players at different positions. Most coaches focus mainly on the external movement structure in practice, while the understanding of the intrinsic mechanisms is insufficient [19]. Meanwhile, existing studies tend to ignore the effect of positional specialization when analyzing volleyball jumps, and are unable to reveal the unique movement patterns formed by different positional players to adapt to their respective tactical demands [20]. Surface electromyography (sEMG) combined with three-dimensional kinematic analysis provides a comprehensive way of exploring the mechanisms underlying complex movement patterns. Simultaneous measurement of muscle activation states and joint kinematic parameters provides insight into the neuromuscular control strategies employed by players in different positions and their impact on performance [21].

Based on the above background, this study aimed to comparatively analyze the lower limb kinematic characteristics and muscle activation patterns of the OHs attacker and OPPs during the spike jump, focusing on the biomechanical parameter changes from the final step of the approach phase to the take-off phase. Specific objectives included: to comparatively analyze the differences in lower limb kinematic parameters between the two positional players at the critical time points of the spike jump; to compare the muscle activation characteristics of the two positional players during the braking phase and the propulsion phase; and to explore the relationship between the positional-specific locomotor patterns and tactical demands. By revealing the position-specific adaptations in spike jump performance between OHs and OPPs, this study aims to provide more precise theoretical guidance for volleyball-specific training, offer a scientific basis for developing targeted position-specific strength and conditioning programs, and present new insights for technical optimization and injury prevention in volleyball.

2. Materials and methods

2.1 Participants

In May 2022, we recruited 12 National Level-1 Volleyball Players, including six OHs and six OPPs, for this study. The OH group had a mean age of 23.25 ± 1.26 years, height of 186.75 ± 4.99 cm and body weight of 78.75 ± 7.89 kg. The OPP group had a mean age of 23.50 ± 1.91 years, height of 191.00 ± 5.48 cm and body weight of 77.75 ± 11.62 kg. All participants were right-handed and right-leg dominant, as determined by the Waterloo Foot Questionnaire Revised (WFQ-R). To ensure the reliability of the study results, all participants had no history of injury or illness for at least one year prior to testing, had not engaged in strenuous physical activity or consumed alcohol in 24 hours prior to testing, and had completed their last meal at least 2 hours prior to testing.

Inclusion criteria included (a) having at least 5 years of professional training experience in volleyball; (b) training at least 16 hours per week; (c) no history of upper or lower extremity or trunk injuries (*e.g.*, shoulder injuries, elbow pain, wrist sprains, ankle sprains, knee ligament injuries, hip injuries or low back pain) in the past 12 months; (d) no neurological disorders that interfere with motor function; and (e) body mass index (BMI) between 18.5 and 25.0 kg/m^2. Exclusion criteria included (a) a serious injury or illness requiring more than 2 weeks of rest in 6 months prior to the test, (b) current pain or discomfort that could interfere with test performance, and (c) a chronic condition requiring long-term medication.

The purpose of the study, tasks, procedures and standard requirements were explained in detail to all participants prior to the experiment, written informed consent was obtained and participation was voluntary. The study followed the principles of the Declaration of Helsinki and was approved by the Research Ethics Committee of Yanshan University (Time: 2022-0302).

2.2 Experimental design

The experiment was based on a real match scenario in which the participants executed a standard spiking maneuver according to the characteristics of their respective positions: the OHs performed a front-row attacks at the No. 4 position, and the OPPs executed a back-row attack at the No. 1 position. In order to improve the internal validity of the study, the following conditions were strictly controlled: testing environment, setter position and setting quality, number of tests and intervals between them, flow of preparatory activities and designated attack area. The complete process of each spiking action from the moment the right foot made ground contact in the final step of the approach to the instant both feet left the ground was recorded and analyzed. This process was divided into a braking phase and a propulsion phase, according to the kinematic characteristics, in order to deeply investigate the technical differences between players at different positions in each phase. While the spike task was standardized to ensure control over experimental variables, it did not include contextual game stimuli such as blockers, spectators or match-induced psychological pressure. This may reduce the ecological validity of the movement, although the setting was designed to replicate typical in-game approach mechanics as closely as possible.

As shown in Fig. 1, the test was conducted on a standard volleyball court with eight Qualisys A12 infrared high-speed motion capture cameras (Qualisys AB, Gothenburg, Sweden; technical specifications available at www.qualisys.com) arranged around the calibration area. Cameras 1 and 8 were positioned at a height of 0.5 m and faced upwards to capture frontside marker point trajectories; cameras 2 and 7 were positioned at a height of 1.8 m and angled horizontally to capture frontside and side marker points; and cameras 3 to 6 were also positioned at a height of 1.8 m to capture side and backside marker points. The camera layout was specifically adapted to the take-off positions and approach routes of the players in different positions to ensure that the entire action was captured in its entirety.

The origin coordinates and range of motion were calibrated prior to testing using the Qualisys spatial calibration accessory (L-frame and calibration bar). As shown in Fig. 2, the coordinate axes were defined as: X-axis parallel to the center line of the volleyball court, pointing to the participant's right sideline; Y-axis parallel to the sideline of the volleyball court, pointing to the bottom line in front of the participant; and Z-axis perpendicular to the ground, pointing upward. This coordinate system setting ensured consistency and comparability of data across all participants.

2.3 Testing procedures

2.3.1 Testing environment setup

This study was conducted on a standard volleyball court. Eight Qualisys A12 infrared high-speed motion capture cameras were arranged around the court to form a complete three-dimensional capture space. The camera arrangement took into account the starting positions and approach routes of the players in two different positions to ensure that the entire test movement could be captured completely. The setter was positioned between positions 2 and 3 to provide standardized passes for the OHs and OPPs.

2.3.2 Preparatory activities

All participants performed standardized preparatory activities, including a 15-minute voluntary warm-up (jogging, dynamic stretching and specialized warm-up). After warming up, participants wore uniform testing attire (tight-fitting short-sleeved top, shorts and volleyball-specific shoes) to minimize the effect of clothing on motion capture. This was followed by a 3-snap trial jump to familiarize themselves with the testing environment and task requirements.

2.3.3 Testing task

Participant Preparation: After completing the spatial calibration, reflective marker dots were attached to the participant's corresponding anatomical marker points (as shown on the left in Fig. 3). Participants executed static postures at the calibrated origin coordinates (shown on the right in Fig. 3) to establish a

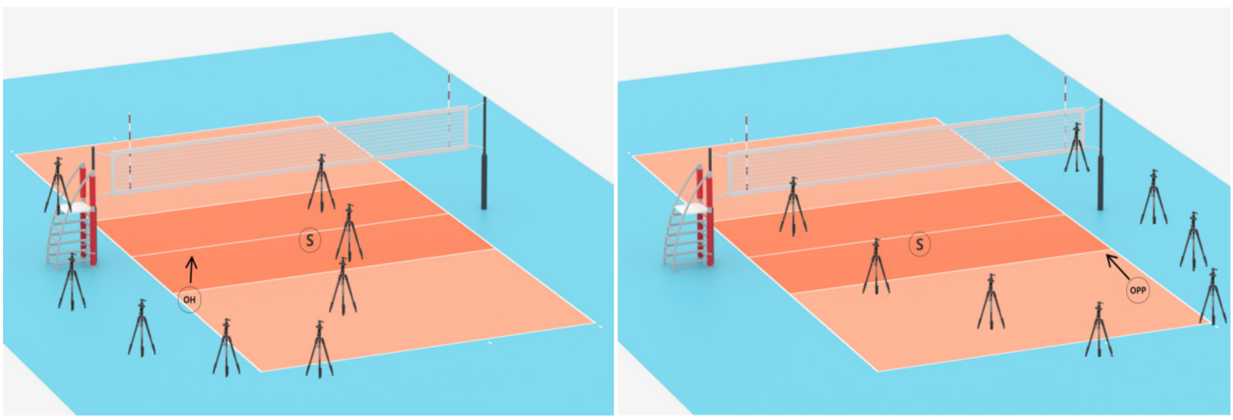

FIGURE 1. Camera setup schematics: on the left side is the OH position, while on the right side is the OPP position. OH: Outside Hitter; OPP: Opposite Hitter; S: Setter; Solid Arrows: Approach direction.

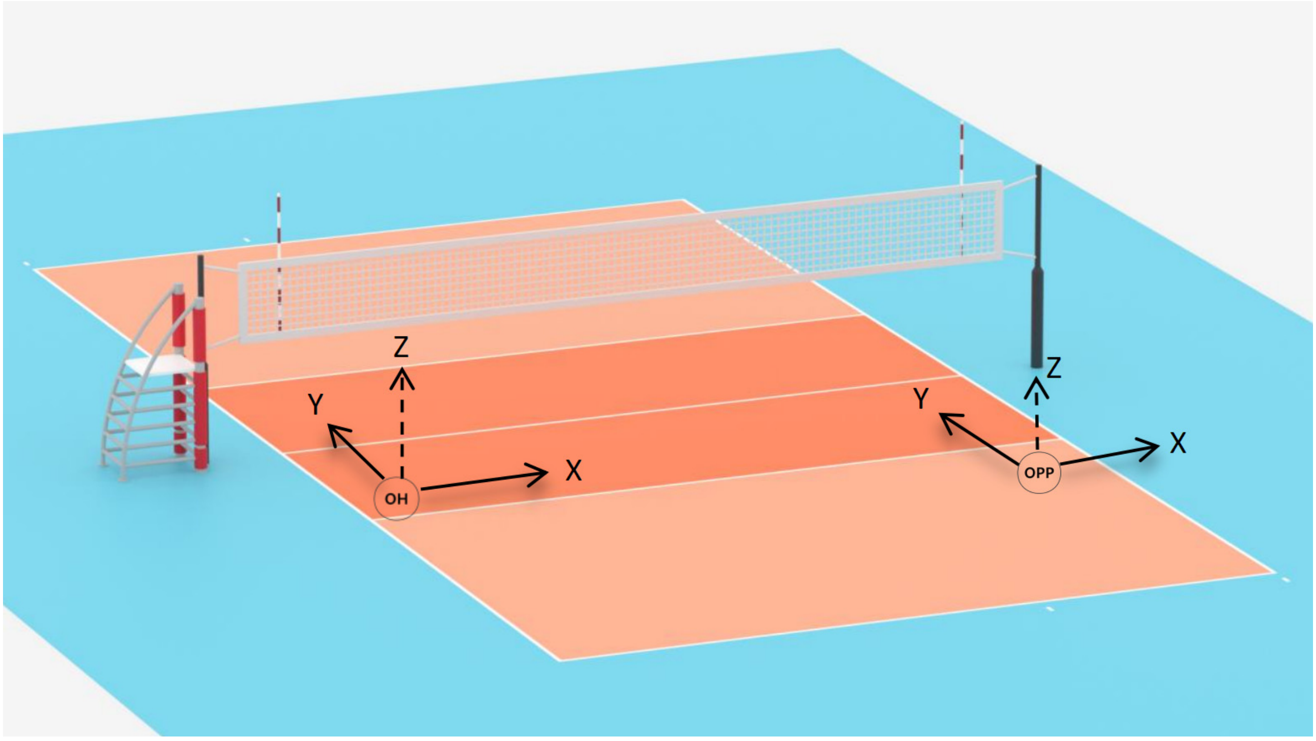

FIGURE 2. Coordinate system origin location. OH: Outside Hitter; OPP: Opposite Hitter.

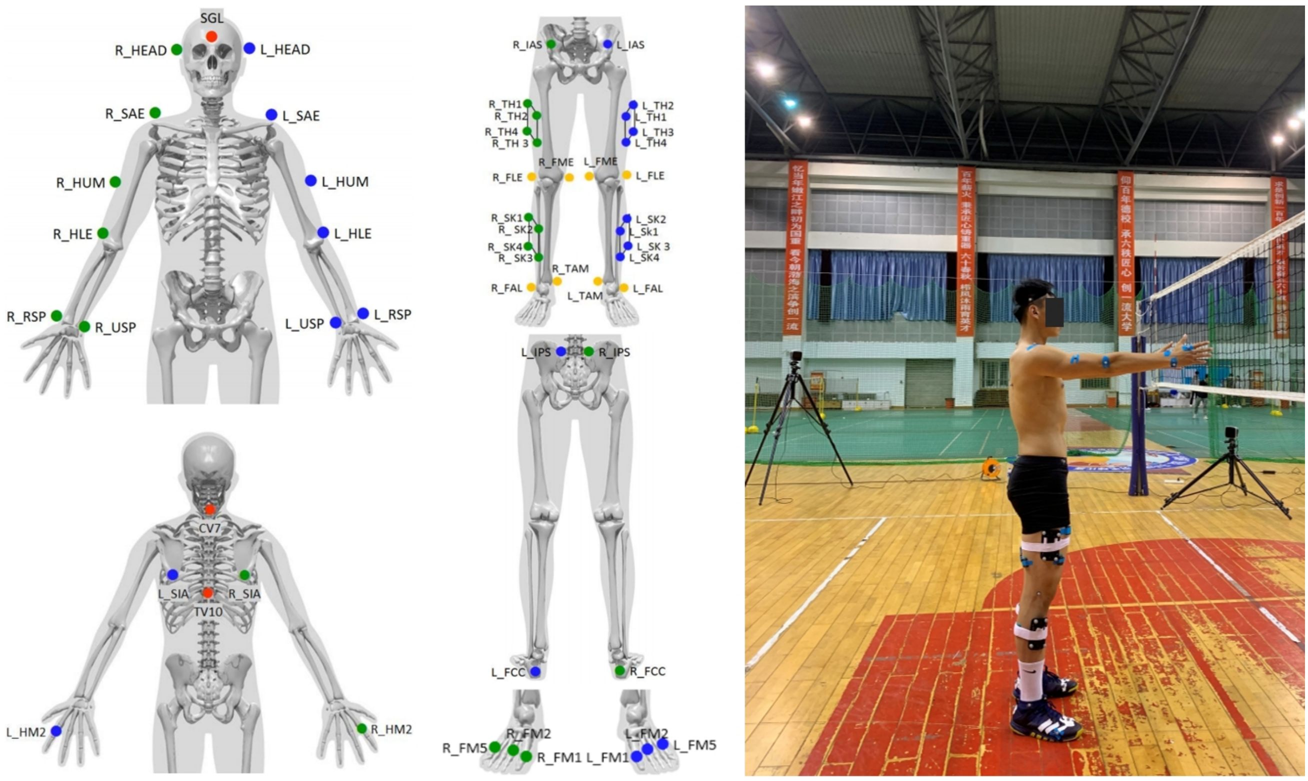

FIGURE 3. Marker placement protocol (Left side) and static calibration posture (Right side).

baseline model. Participants were then prepared to execute the spike jump maneuver according to their respective positional requirements.

The testing task was determined based on each participant's court position:

OH from position 4, receives a pass from the setter and completes a standard three-step approach jump front-row spike, with the direction of attack being the No. 5 area of the opposing team's field.

OPP: Starting from position 1, receives a pass from the setter and completes a standard three-step approach jump back-row attack, with the direction of attack being the No. 1 and No. 6 areas of the opposing team's court.

As shown in Fig. 4, the setter was located between positions

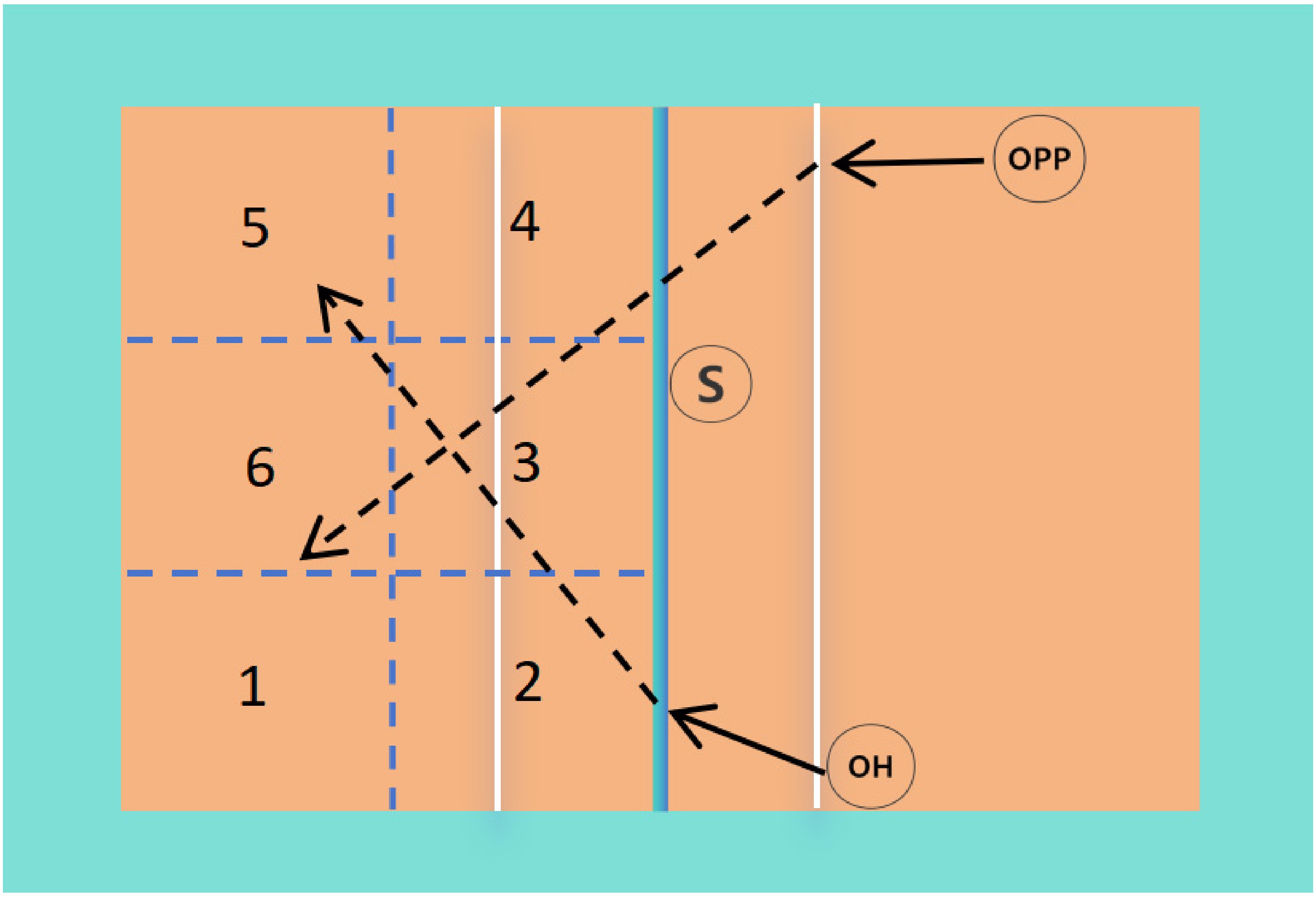

FIGURE 4. Effective attack zone. S: Setter position; OH: Outside hitter position; OPP: Opposite hitter position; Solid arrow: Approach direction; Dashed arrow: Spike trajectory.

2 and 3. The participant first passes the ball to the setter, who passes the ball according to the participant's position and test requirements. The starting position of the OH is at position 4, executing power Spike and attacking in the direction of the opponent's position 5 area, while the starting position of the OPP is at position 1, executing back-row attacks and attacking in the direction of the opponent's position 1 and 6 areas.

Each participant completed six formal spiking attempts in accordance with the above requirements, each separated by 90 seconds to ensure adequate recovery and movement quality. Three volleyball experts with national referee qualifications made technical assessments of each spike, including the quality of the approach, the jump height, the timing of the stroke, the smoothness of the movement, the effectiveness of the attack and the direction of the attack. The one with the highest technical score was selected as the final sample for analysis. However, all attempts were recorded and retained for potential future analysis. These additional trials may provide valuable insights into individual variability, suboptimal technique patterns and position-specific movement deficiencies, which we plan to explore in subsequent publications.

2.3.4 Division of the movement

As shown in Fig. 5, the analyzed movement is divided into four key time points and two phases, starting from the landing of the right foot in the last step of the approach and ending with the feet leaving the ground: T1: the landing moment of the right foot (the last step of the approach); T2: the landing moment of the step-up foot; T3: the moment of reaching the maximum angle of flexion of the right knee joint (transition point); T4: the moment when the feet leave the ground.

Based on these four key time points, the entire jump is divided into two functional phases: Braking phase (T1–T3): slowing down the horizontal velocity and reserving the elastic energy; and Propulsion phase (T3–T4): transforming the reserved elastic energy into vertical propulsion force.

2.4 Data collection

2.4.1 Kinematic data collection

In this study, kinematic data were collected using a Qualisys A12 infrared high-speed motion capture system, which consisted of eight high-speed cameras with a sampling frequency of 240 Hz. The system was calibrated using the Qualisys standard calibration program, and the residual values were controlled to be less than 0.8 mm to ensure the accuracy of the measurements. For accuracy, forty-seven 14 mm diameter reflective markers were attached to the participant's body, based on the CAST Marker Set whole-body model, covering key anatomical landmarks on the torso, pelvis and upper and lower extremities. The kinematic data were recorded in real time using Qualisys Track Manager (QTM) software (version

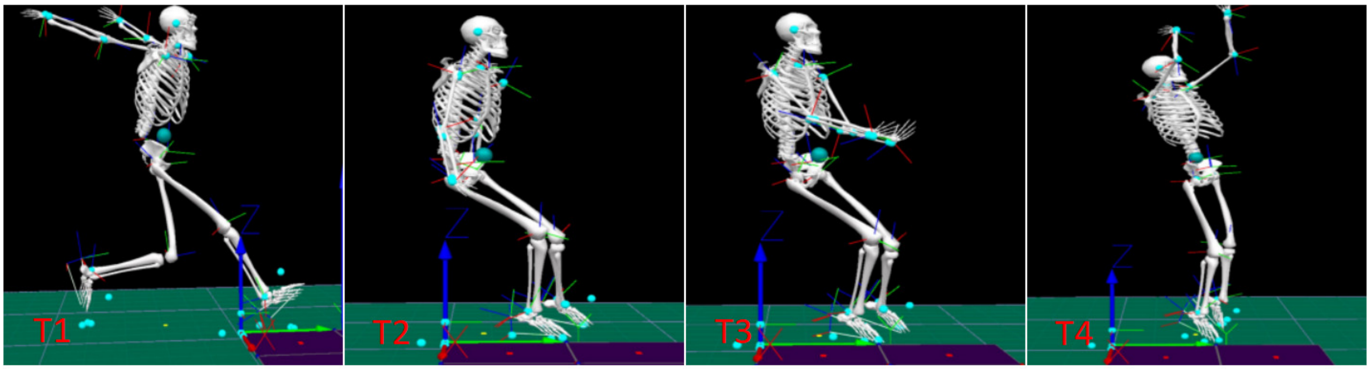

FIGURE 5. Motion characteristics at four key time points. T1–T3: Braking Phase; T3–T4: Propulsion Phase.

2019.3, Qualisys AB, Gothenburg, Sweden) and then imported into Visual3D for processing and analysis.

The kinematic parameters analyzed included: right knee joint angle, landing angle, take-off angle, step-close foot angle, shoulder joint line angle, distance between center of mass projection and support point, distance between right foot and center of mass projection, distance between feet, right knee angular velocity, duration of the braking phase and duration of the Propulsion phase. All joint angle data were processed through a Butterworth low-pass filter with a cutoff frequency of 10 Hz to eliminate high-frequency noise.

2.4.2 sEMG data collection

Surface electromyographic (sEMG) data were collected using the Delsys Trigno wireless sEMG system (Delsys Inc., Natick, MA, USA; technical details available at www.delsys.com), with a sampling frequency of 2000 Hz for each sensor. Before attaching the electrodes, a thorough skin preparation protocol was followed: hair was removed if necessary, the skin was cleaned and disinfected with medical alcohol, a conductive gel was applied to enhance conductivity, and the skin surface was wiped clean and dried.

Wireless surface electrodes were placed on the major force-generating muscles of the lower limbs of the participant's bilateral limbs, including the gluteus maximus, rectus femoris, vastus medialis, vastus lateralis, semitendinosus, lateral head of gastrocnemius and tibialis anterior, according to electrode positions recommended by the international standard of SENIAM (Surface Electromyography for Non-Invasive Assessment of Muscles), lateral head of gastrocnemius and tibialis anterior. The electrodes were placed at a standard 20 mm distance from each other, aligned with the direction of the muscle fibers and secured to the muscle belly of each muscle. The electrodes were securely fastened with medical tape and muscle tape to prevent displacement during exercise.

Raw EMG signals were processed using a second-order Butterworth digital filter with a 10–450 Hz bandpass filter to remove possible motion artifacts and power disturbances, followed by full-wave rectification and root mean square (RMS) smoothing (window width 100 ms). Integral electromyogram (iEMG) values were calculated for each muscle during the braking phase (T1 to T3) and the propulsion phase (T3 to T4), and the relative percentage contribution of each muscle was calculated to quantify the activation levels and synergistic patterns of the different muscles during the spike jump. Due to the dynamic nature of the spike movement and practical limitations, EMG signals were not normalized to maximal voluntary contractions (MVC). Instead, comparisons were made using iEMG contributions expressed as relative percentages within and across movement phases, a method previously used in similar volleyball EMG research [22].

2.5 Statistical analysis

All data were statistically analyzed using SPSS 22.0 software (version 22.0, IBM Corp., Armonk, NY, USA). The data were first subjected to descriptive analysis and the results were expressed as mean ± standard deviation (mean ± SD). The Shapiro-Wilk test was used to confirm normal distribution of the data and variance alignment was assessed by Levene's test, and the results are presented in **Supplementary material**. Comparisons of kinematic parameters and electromyographic characteristics between the two groups (OH and OPP) were performed using the independent samples t-test. Given the relatively small sample size (n = 12), Cohen's d was calculated to assess the effect size of the group differences, helping to quantify the magnitude of observed effects. Effect size values of 0.2, 0.5 and 0.8 were interpreted as small, medium and large, respectively.

3. Results

3.1 Kinematic characteristics of spike jump by outside hitter and opposite hitter

3.1.1 Movement characteristics at T1

As shown in Fig. 6, at the T1 stage, the Right Foot Landing Angle of the OPP group (53.13° ± 2.89°) was significantly greater than that of the OH group (37.07° ± 4.17°), $p < 0.05$. Although there was no significant difference in Landing Angle between the two groups, the OH group exhibited a slightly higher mean value. In contrast, the Distance Between Center of Mass Projection and Support Point in the OPP group (0.624 ± 0.032 m) was also significantly greater than that of the OH group (0.549 ± 0.032 m, $p < 0.05$), suggesting that the OPP group had a stronger forward body movement in the preparatory phase of the Approach Jump.

3.1.2 Characteristics of movement at T2 moment

As shown in Fig. 7, at the T2 moment, the OPP's Shoulder Joint Line Angle was significantly smaller than that of the OH (OPP: 19.43° ± 8.62°, OH: 49.49° ± 8.57°, $p < 0.01$). The Distance Between Right Foot and Center of Mass Projection of the OPP was significantly greater than that of the OH (OPP: 0.27 ± 0.08 m, OH: 0.01 ± 0.02 m, $p < 0.05$), and the Inter-foot distance was also significantly greater than that of the OH (OPP: 0.84 ± 0.05 m, OH: 0.56 ± 0.05 m, $p < 0.01$).

3.1.3 Kinematic characteristics at T3

As shown in Fig. 8, the Left Knee Joint Angle of the OH was 137.00° ± 6.61°, and that of the Right Knee Joint Angle was 93.93° ± 10.78°; and the Left Knee Joint Angle of the OPP was 142.65° ± 5.05°, and that of the Right Knee Joint Angle was 88.15° ± 5.20°, both of which demonstrated the characteristics of the left side being larger than that of the right side. The differences were not significant in terms of Braking Phase Duration (OH: 0.27 ± 0.01 s; OPP: 0.26 ± 0.03 s) and right knee angular velocity (OH: 199.45 ± 20.87 °/s; OPP: 231.1 ± 25.42 °/s). Right knee angular velocity was slightly higher for the OPP (231.1 ± 25.42 °/s) compared to the OH (OH: 199.45 ± 20.87 °/s), possibly reflecting the OPP's greater explosive power of knee extension during this phase, but the difference was not significant.

3.1.4 Kinematic characteristics at T4

As shown in Fig. 9, at the T4 moment the OH's Take-off angle was greater than that of the OPP (70.34 ± 2.54 *vs.* 57.95 ± 2.65, $p < 0.01$), while the Propulsion phase duration was less than that of the OPP (0.13 ± 0.01 *vs.* 0.17 ± 0.01), ($p < 0.01$).

3.2 Integrated EMG (iEMG) results and analysis of lower limb muscles in outside and opposite hitters

3.2.1 iEMG analysis of lower limb muscles during the braking phase

Table 1 shows that the activation level of the right leg muscle groups of the OH was higher than that of the left leg in the Braking phase as a whole. The primary contributing muscles on the right leg included the Vastus lateralis, Vastus medialis, Tibialis anterior and Rectus femoris, with Relative iEMG contribution percentages of 20.04%, 14.44%, 10.87% and 8.01%, respectively, totaling 53.35%. The right leg carried greater support and cushioning loads, consistent with its center of gravity shift pattern. The OPP also demonstrated an overall higher level of muscle activation in the right leg than in the left

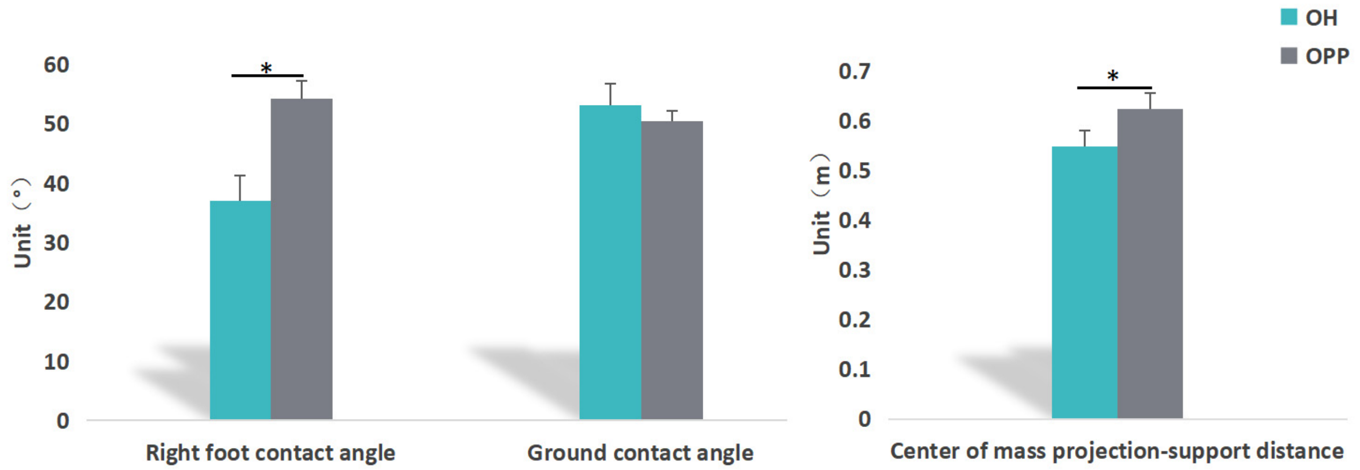

FIGURE 6. Kinematic signatures at T1. *: ($p < 0.05$). OH: Outside hitter position; OPP: Opposite hitter position.

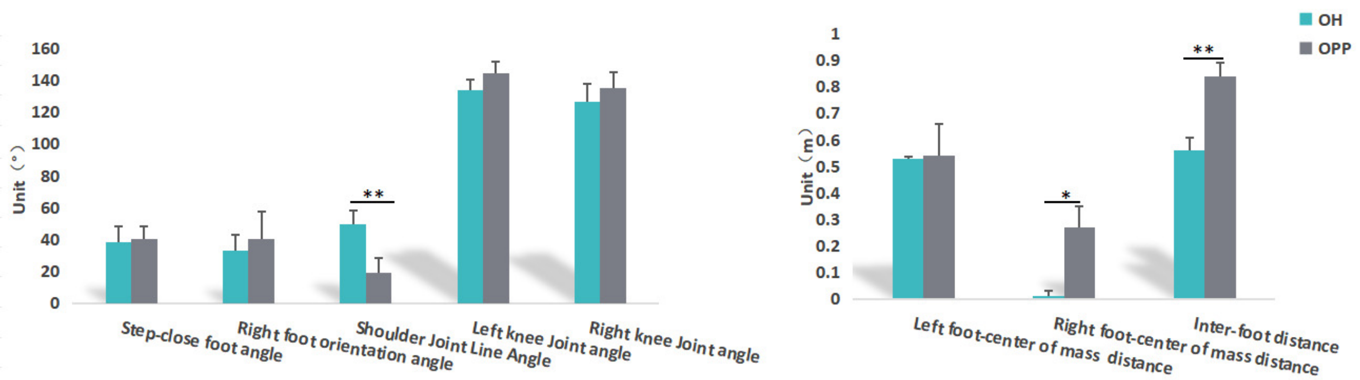

FIGURE 7. Kinematic signatures at T2. **: ($p < 0.01$); *: ($p < 0.05$). OH: Outside hitter position; OPP: Opposite hitter position.

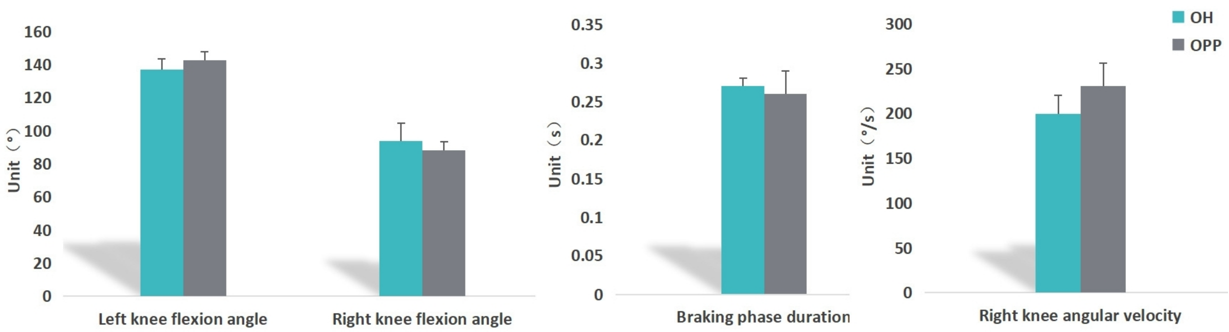

FIGURE 8. Kinematic signatures at T3. OH: Outside hitter position; OPP: Opposite hitter position.

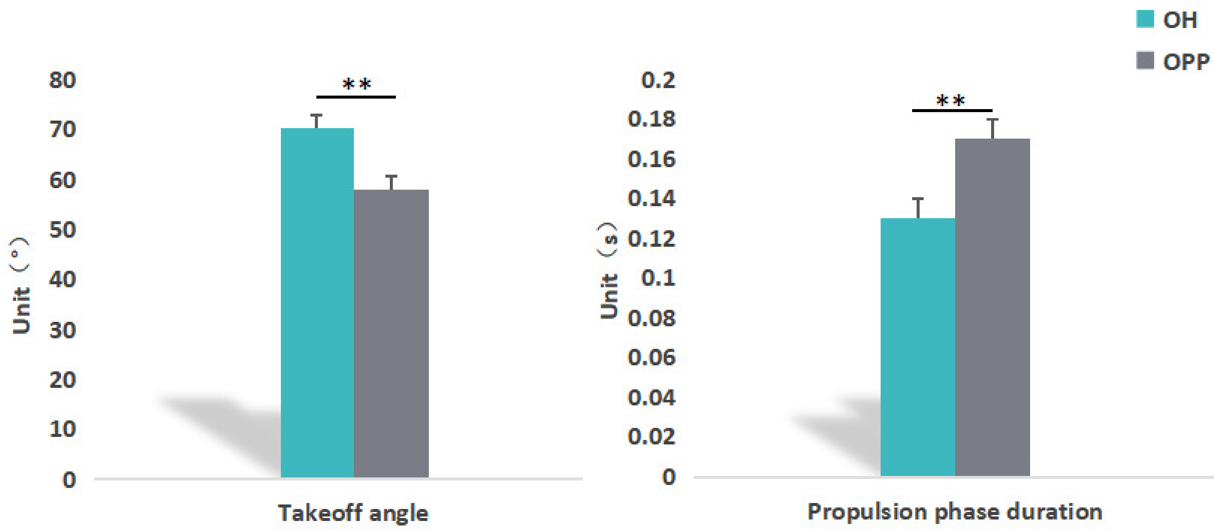

FIGURE 9. Kinematic signatures at T4. **: ($p < 0.01$). OH: Outside hitter position; OPP: Opposite hitter position.

TABLE 1. Integrated EMG values of lower limb muscle groups in each phase of the braking phase (Unit: μVs).

Muscle Names	Outside Hitter		Opposite Hitter	
	Left Leg	Right Leg	Left Leg	Right Leg
Gluteus maximus	1.18 ± 0.58	3.88 ± 1.46	0.66 ± 0.06	5.03 ± 1.26
Rectus femoris	3.73 ± 0.77	5.58 ± 3.30	2.05 ± 0.84	8.03 ± 1.20
Vastus medialis	4.28 ± 1.37	9.24 ± 1.70	2.84 ± 1.00	8.70 ± 1.42
Vastus lateralis	4.02 ± 0.90	13.34 ± 4.33	3.36 ± 1.09	16.42 ± 3.43
Semitendinosus	2.39 ± 0.96	2.98 ± 1.09	2.76 ± 0.68	4.67 ± 2.74
Lateral head of gastrocnemius	1.62 ± 0.09	2.73 ± 1.02	5.15 ± 1.46	7.93 ± 1.38
Tibialis anterior	3.42 ± 0.76	7.02 ± 1.93	3.75 ± 0.67	8.51 ± 0.15

leg. The Vastus lateralis, Vastus medialis, tibialis anterior, and rectus femoris of the right leg were the main force-generating muscles, contributing 20.81%, 11.01%, 10.85% and 10.26%, respectively, totaling 53.02%, which is in line with the OPP's pattern of using the right leg as the main supporting leg.

3.2.2 iEMG analysis of lower limb muscles during the propulsion phase

Table 2 shows that the activation level of the left leg muscle groups was generally higher than that of the right leg during the OH Propulsion phase, with the Vastus lateralis, Vastus medialis and the lateral head of gastrocnemius of the left leg as the main force-generating muscle groups. The contributions were: 17.62%, 15.37%, and the lateral head of gastrocnemius muscle of both legs (9.88% on the left and 9.32% on the right) totaling 52.18%. The higher contribution of the lateral head of gastrocnemius indicates its important role in generating propulsive force during take-off. The OPP's left leg similarly showed a higher level of muscle activation. The Vastus lateralis, rectus femoral, Vastus medialis, and gluteus maximus muscles of the left leg all showed left leg activation dominance. The overall contribution of the major force-generating muscle groups was 61.69%; the Vastus lateralis (13.73%), rectus femoris (8.75%), semitendinosus of both legs (left: 9.02%, right: 12.69%) and

TABLE 2. Integrated EMG values of lower limb muscle groups in each phase of the propulsion phase (Unit: μVs).

Muscle Names	Outside Hitter		Opposite Hitter	
	Left Leg	Right Leg	Left Leg	Right Leg
Gluteus maximus	1.32 ± 0.90	0.73 ± 0.32	2.24 ± 0.42	0.66 ± 0.09
Rectus femoris	2.15 ± 0.62	1.34 ± 0.90	2.67 ± 0.48	0.68 ± 0.21
Vastus medialis	5.03 ± 1.80	1.48 ± 0.43	2.36 ± 0.47	1.72 ± 0.61
Vastus lateralis	5.42 ± 1.44	2.40 ± 0.63	4.50 ± 2.42	1.91 ± 0.67
Semitendinosus	1.07 ± 0.22	1.77 ± 0.73	2.76 ± 0.62	4.17 ± 1.30
Lateral head of gastrocnemius	3.11 ± 1.27	2.86 ± 0.74	2.73 ± 0.86	2.78 ± 0.96
Tibialis anterior	1.50 ± 0.97	0.78 ± 0.50	1.54 ± 0.35	0.65 ± 0.20

lateral head of gastrocnemius (left: 8.70%, right: 8.79%). The high contribution of the semitendinosus reflects the unique muscle group force pattern of the OPP during the Propulsion phase.

4. Discussion

The most significant finding of this study was the distinct neuromuscular activation and kinematic differences between OH and OPP players during the spike jump. Specifically, OPP players exhibited significantly greater bilateral iEMG activity during the propulsive phase, whereas OH players demonstrated greater asymmetry in ground contact and muscle activation. These differences may be attributed to the distinct tactical roles and repetitive movement patterns required by each position. OPP players, being more attack-oriented, likely develop more symmetrical and forceful jump mechanics, while OH players frequently perform transitions between defense and offense, resulting in more variable and unilateral loadings.

At T1, the right foot contacts the ground while the left lower limb remains in a follow-through swing phase. The Right Foot Landing Angle refers to the angle formed between the right foot and the court centerline at landing, which reflects the body's facing direction relative to the net [23]. The Landing Angle, defined as the angle between the line connecting the center of mass and the support point and the ground, determines the magnitude of the ground reaction forces in both horizontal and vertical directions [4, 24]. The Right Foot Landing Angle and the Distance Between Center of Mass Projection and Support Point are significantly greater in OPPs compared to OHs, indicating a more frontal orientation toward the net and a longer step length during the take-off preparation phase. T2 represents the moment when the step-close foot contacts the ground, marking the transition from unilateral to bilateral support. The Step-close foot angle is defined as the angle between the left foot and the court centerline, while the Shoulder Joint Line Angle refers to the angle between the line connecting the bilateral shoulder joints and the net. Both the Inter-foot distance and the Distance Between Right Foot and Center of Mass Projection are significantly greater in OPPs than in OHs, indicating a longer step-close distance. Although the Right foot angle of OPPs is not significantly greater, their Shoulder Joint Line Angle is significantly smaller than that of OHs, further suggesting a more frontal body orientation toward the net. T3 represents the critical moment when the Right Knee Joint Angle reaches its minimum value, marking the transition between the Braking phase and the Propulsion phase, during which horizontal velocity is converted into vertical velocity [25]. At this moment, both OHs and OPPs exhibit greater Left Knee Joint Angle than Right Knee Joint Angle, with the latter further decreasing, indicating an increased degree of right knee flexion and enhanced buffering. The Right knee angular velocity of OPPs is greater than that of OHs, while their Braking phase duration is shorter. This is attributable to the fact that OHs take off closer to the net and require longer braking to control horizontal displacement, whereas OPPs initiate take-off from a further distance, thus maintaining more forward momentum with reduced braking. T4 marks the moment of take-off when both feet leave the ground. Under constant center of mass and velocity, a greater Take-off angle corresponds to a higher vertical velocity component, which directly influences Jump height [26, 27]. The Take-off angle of OPPs is significantly smaller than that of OHs, whereas their Propulsion phase duration is significantly longer, indicating that OPPs cover a longer displacement and possess greater upward acceleration space during the Propulsion phase. In summary, the difference in knee joint angles between the left and right legs during the Braking Phase is larger for both OHs and OPPs, with the right leg being the primary supporting leg. During the spike jump of the OPP, the angle between both feet and the court centerline is greater compared to the OH, while the angle between the shoulder joint line and the court centerline is smaller, indicating a greater frontal orientation toward the net. This aligns with the OPP's more variable attacking routes. Furthermore, the OPP exhibits a smaller take-off angle, longer forward momentum distance [28], shorter Braking Phase duration, longer Propulsion Phase duration, and a higher right knee angular velocity, which satisfies the dual demands of jump height and forward distance for back-row attacks [29]. However, the right knee joint experiences greater stress during the jump, which increases the risk of injury. In contrast, the OH has a slightly larger take-off angle, shorter Propulsion Phase duration, and although there is some forward momentum, the focus is more on maximizing jump height to reach a higher hitting point and avoid the opponent's block [30].

Both the OH and OPP undergo a center of mass transfer process from the Braking Phase to the Propulsion Phase. During the Braking Phase, the right leg serves as the primary supporting leg, with higher muscle activation levels. In the

Propulsion Phase, the left leg dominates the force production, playing a key role in decelerating the horizontal velocity and converting it into vertical velocity [31]. This coordinated pattern of muscle activation and center of mass transfer facilitates the efficient conversion of kinetic energy into potential energy. In the Braking Phase, the force production patterns of both the OH and OPP are similar, primarily relying on the right leg's vastus lateralis, vastus medialis, tibialis anterior and rectus femoris. The vastus medialis and vastus lateralis work in a concentric contraction to stabilize the knee joint in the sagittal and coronal planes while storing elastic potential energy. During ankle dorsiflexion, the tibialis anterior undergoes eccentric contraction to stabilize the ankle joint and ensure foot support. The rectus femoris also undergoes eccentric contraction during knee flexion to control the range of motion at the knee joint and store elastic potential energy. In the Propulsion Phase, the force production patterns of the OH and OPP differ. The primary muscles involved for the OH are the left leg's vastus medialis, vastus lateralis and lateral head of the gastrocnemius, while the OPP relies on the left leg's vastus lateralis, tibialis anterior, semimembranosus and lateral head of the gastrocnemius. The vastus medialis and vastus lateralis work in concentric contraction to rapidly extend the knee joint, providing the necessary force for take-off. The lateral head of the gastrocnemius contracts to drive ankle plantarflexion, creating an upward reaction force from the ground, thus resulting in upward acceleration. The semimembranosus contracts in coordination with the gluteus maximus and quadriceps to extend the hip and knee, propelling the body into the air. Since the OPP has a longer Propulsion Phase duration and greater vertical displacement in the air, with full hip extension, the semimembranosus contributes significantly during the Propulsion Phase. Based on these characteristics, strength training should be tailored to the specific take-off technique of both the OH and OPP, focusing on the balanced development of lower limb strength in both legs and enhancing the specialized training of the primary muscle groups to optimize take-off performance and reduce the risk of sports injuries [32].

In daily training, the Landing Angle, knee joint Braking Angle, speed, and Propulsion Phase duration should be used as the quality assessment standards for strength training movements. Additionally, specific training should focus on the foot angle, Take-off angle, inter-foot distance and Shoulder Joint Line Angle. Compensatory training to strengthen the right knee joint stability should be implemented to optimize joint load distribution and reduce the risk of injury [33]. Furthermore, attention should be given to reinforcing the concentric contraction training of the left leg muscles during the Propulsion Phase and the eccentric contraction training of the right leg muscles during the Braking Phase [32]. In this, focus should be placed on enhancing strength development of the right leg tibialis anterior during the Braking Phase, the lateral head of the gastrocnemius in both legs during the Propulsion Phase, and the semimembranosus in both legs for the OPP.

In addition to biomechanical and neuromuscular factors, the observed differences between OH and OPP players may also stem from the inherent tactical and technical roles associated with each position [34]. Outside hitters (OH) are typically involved in serve reception and back-row defense, often requiring them to transition quickly between defensive and offensive phases [35]. In contrast, opposite hitters (OPP) are more offensively specialized and are less frequently involved in serve-receive duties. These role-based distinctions can shape habitual movement strategies, muscle activation patterns, and even jump approach techniques over years of training and gameplay [36]. Therefore, the positional differences in spike biomechanics observed in this study may partly reflect long-term adaptations to distinct tactical demands.

Although these practical recommendations stem from our observations, some limitations should be recognized when interpreting the findings and considering their application. First, the sample size consisting of 12 national-level male volleyball players (6 OH and 6 OPP) was relatively small. This may limit the generalizability of our findings to a wider group of elite volleyball players. Although the participants represented a high level of expertise, there are still considerations to be made when extrapolating these specific kinematic and neuromuscular patterns to a larger group. Second, the homogeneity of the sample means that the findings may not be directly applicable to female volleyball players, who typically exhibit different biomechanical and strength characteristics, or to athletes competing at sub-elite or developmental levels. Future research involving larger and more diverse samples, including female athletes and athletes from different competitive tiers, would be beneficial in confirming and extending these findings. Finally, snapping was performed under controlled experimental conditions. While this approach ensures standardization and reduces confounding variables, it may not fully replicate the complex and variable environment of an actual competitive match, which includes factors such as psychological stress, variable set quality, interactions with blockers and specific tactical situations. As a result, performance characteristics observed in such controlled environments may differ from those exhibited in actual games. Nonetheless, despite these limitations, the detailed biomechanical and neuromuscular insights provided by this study offer valuable practical implications. Coaches and strength and conditioning professionals can utilize the findings to develop more targeted training protocols for Outside and Opposite Hitters. For instance, Opposite Hitters may benefit from focused eccentric control and right-leg stabilization training, while Outside Hitters may prioritize optimizing vertical explosiveness and take-off mechanics. Furthermore, understanding asymmetric muscle activation patterns and joint loading characteristics allows for the design of personalized injury prevention strategies. These findings can serve as a foundation for enhancing performance and training specificity in elite volleyball settings.

5. Conclusions

During the Approach Jump of the Opposite Hitter, the body orientation towards the net is greater, with a longer stride during the last step and a greater forward distance after takeoff, resulting in higher load on the Right Knee Joint. In contrast, the Outside Hitter has a shorter forward distance during takeoff, focusing more on Jump Height to achieve a higher Hit Point. The Opposite Hitter, on the other hand, needs to balance both Jump Height and forward distance to accommodate the dynamic requirements of the attack.

Both the Outside and Opposite Hitter exhibit significant differences in the Knee Joint Angles between the left and right legs during the Braking Phase, with the Right Leg dominating the force generation and the Left Leg taking over during the Propulsion Phase, reflecting a pattern of single-leg support, Center of Mass transfer and asymmetric force production. The Vastus Medialis and Vastus Lateralis make substantial contributions during all phases, with the Rectus Femoris and Tibialis Anterior also playing significant roles in the Braking Phase. During the Propulsion Phase, the Lateral Head of Gastrocnemius in the Outside Hitter and the Semitendinosus and Lateral Head of Gastrocnemius in the Opposite Hitter are key contributors, representing the primary force-generating muscle groups for the Propulsion action.

AVAILABILITY OF DATA AND MATERIALS

Due to ethical and institutional constraints outlined in the informed consent process, data sets generated and analyzed during this study will not be made publicly available. However, anonymized summary-level data or specific data segments are available upon reasonable request to the corresponding author.

AUTHOR CONTRIBUTIONS

CC and JLZ—conceptualization. ZNZ—methodology. YW—software. HY, KYH and CC—validation. JLZ—investigation. MLD—resources; YWSG—writing-review and editing. HY—data curation. CC—writing-original draft preparation. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Research Ethics Committee of Yanshan University (Time: 2022-0302). All participants voluntarily participated in this study and signed written informed consent forms, including agreement for the use of their photos and data for academic publication purposes.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

SUPPLEMENTARY MATERIAL

Supplementary material associated with this article can be found, in the online version, at https://oss.jomh.org/files/article/1938531679470534656/attachment/Supplementary%20material.docx.

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