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ORIGINAL RESEARCH

Asymmetrical lower-limb injury risk during the volleyball spike jump of male elite volleyball players

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Abstract

Background: Repetitive high-intensity spike jumps (SPJs) impose substantial mechanical loading on the lower limbs and are associated with overuse and acute injuries, such as patellar tendinopathy, anterior cruciate ligament (ACL) injury, and lateral ankle sprain. Asymmetries between the dominant leg (DL) and non-dominant leg (N-DL) during take-off may create leg-specific loading profiles. This study examined how each limb generates and transfers mechanical energy during the take-off phase of the SPJ. **Methods**: Eleven male collegiate volleyball athletes performed SPJs while three-dimensional lower-limb joint power was analyzed during take-off. Total energy generation and inter-joint energy transfer were quantified separately for the DL and N-DL. **Results**: The DL generated significantly more total energy (p = 0.002, d = 1.27), initiated production earlier, and maintained energy generation for a longer duration. In contrast, the N-DL transferred significantly more energy through the hip, knee, and ankle joints (p = 0.005, d = −1.08). Despite these magnitude differences, both limbs exhibited similar relative hip, knee, and ankle contribution patterns, indicating a coordinated bilateral strategy to produce vertical impulse and stabilize take-off. **Conclusions**: Greater knee and ankle extensor output in the DL may increase exposure to loading patterns associated with patellar tendinopathy and Achilles tendon overload, whereas the N-DL's larger horizontal-to-vertical energy transfer may increase exposure to ACL-related knee loading and lateral ankle sprain mechanisms. These findings support limb-specific preventative strategies (*e.g.*, eccentric strengthening for the DL and neuromuscular control training for the N-DL) to manage SPJ loading demands.

Keywords

Patellar tendinopathy; Achilles tendon; ACL strain; Lateral ankle sprain; Energy flow

1. Introduction

Repetitive high-intensity spike jumps (SPJs) are among the most mechanically demanding actions in men's volleyball and have been associated with lower limb loading patterns linked to conditions such as anterior cruciate ligament (ACL) rupture, patellar tendinopathy, patellofemoral pain, and chronic ankle instability [1–6]. Each SPJ requires the athlete to rapidly decelerate from the approach run and then immediately reaccelerate vertically to execute the attack [7]. This rapid deceleration and subsequent acceleration sequence generates ground reaction forces several times greater than the body weight and produces large multiplanar joint torques, placing the hip, knee, and ankle under substantial instantaneous loading as well as repeated cumulative stress over time [8, 9].

A key but underexplored factor in these loading patterns is the functional specialization between the lower limbs, rather than simple bilateral asymmetry. The dominant leg (DL) and non-dominant leg (N-DL) adopt distinct mechanical roles: the N-DL typically generates a greater horizontal braking impulse and redirects approach momentum, whereas the DL contributes more vertical propulsion of the center of mass (CoM) during take-off [7, 10, 11]. While this division of labor is advantageous for jump performance, it creates limb specific loading profiles, exposing each limb to different magnitudes and directions of mechanical demand. Repeated high knee and ankle extensor demand in the DL, on one hand, may increase exposure to loading patterns associated with patellar tendinopathy, patellofemoral pain, and Achilles tendon overload. The N-DL, on the other hand, is subjected to greater deceleration forces and frontal plane control demands, which may increase exposure to ACL related knee loading and lateral ankle sprain mechanisms, particularly under fatigued or suboptimal neuromuscular control.

Traditional determinants of SPJ height, including lower-limb strength, approach velocity, center of mass (CoM) displacement, and arm swing dynamics [1, 8, 12, 13], help explain jump performance but do not fully describe how mechanical loading is distributed across the lower limbs. In fact, several performance-enhancing strategies may also increase exposure to loading patterns associated with common injury mechanisms. For example, faster approach speed elevates muscle activation and stretch-reflex responsiveness [14, 15], but it also increases knee extensor torque and ACL-related knee loading. Similarly, adopting a lower CoM position, although beneficial for jump efficiency [16], prolongs the braking phase and elevates cumulative knee extensor demand, a loading profile commonly associated with patellofemoral pain [6, 17].

To clarify these loading-related mechanisms, it is essential to examine how mechanical energy is generated and transferred across the hip, knee, and ankle joints when horizontal approach momentum is converted into vertical take-off motion. Joint energy-flow analysis provides a direct means of characterizing joint-specific loading and intersegmental coordination and of distinguishing between the energy-generation and energy-transfer patterns [18–20]. Previous studies have documented between-limb kinematic and kinetic differences, such as greater joint flexion and higher angular velocities in the dominant take-off leg, as well as side-to-side differences in vertical and horizontal impulses [7, 10]. However, the underlying mechanical energy strategies that may differentially expose each limb to injury-related loading patterns have not yet been fully described.

Accordingly, the present study examines joint-specific energy generation and transfer during the take-off phase of the SPJ in elite male volleyball athletes. By quantifying how the DL and N-DL differ in their mechanical energy strategies, this study aims to characterize limb-dependent loading profiles that are associated with patellar tendinopathy, Achilles tendon disorders, ACL-related knee loading, and lateral ankle sprain/instability. These findings are expected to provide a biomechanical basis for limb-specific, asymmetry-aware load management and injury prevention strategies.

2. Materials and methods

2.1 Participants

A total of 11 elite male collegiate volleyball athletes were recruited between 10 January and 12 February 2025 for this study. Participants had a mean age of 20.4 ± 1.7 years, body mass 79.4 ± 7.1 kg, height 1.89 ± 0.10 m, and training experience 9.0 ± 1.5 years. Inclusion criteria were: (i) currently competing at the collegiate level, (ii) a minimum of 5 years of systematic volleyball training and participation in official competitions, and (iii) the ability to perform spike jumps with full approach and take-off technique. Exclusion criteria were: (i) any musculoskeletal injury or pain in the lower limbs or trunk within the previous 6 months, (ii) a history of lower-limb surgery, and (iii) inability to complete the jump tasks according to experimental requirements. All participants were right-side dominant and reported no musculoskeletal injuries in the 6 months preceding data collection. Prior to participation, all athletes provided written informed consent. The study protocol was approved by the Jeonbuk National University Institutional Review Board (JBNU2024-09-015-002). All participants competed at the elite collegiate level, which supports the ecological validity of the findings for high-performance volleyball settings.

2.2 Preparation for testing

Before the experiment, participants performed familiarization trials to become accustomed to the experimental procedures. An adjustable-height device [7, 10] was used to suspend a ball in front of the net, and the ball was released on contact to standardize the SPJ task and encourage maximal jump height. Each foot was positioned on a separate force platform to allow bilateral ground-reaction-force recording, and successful spikes were required to land in a designated target area (Fig. 1).

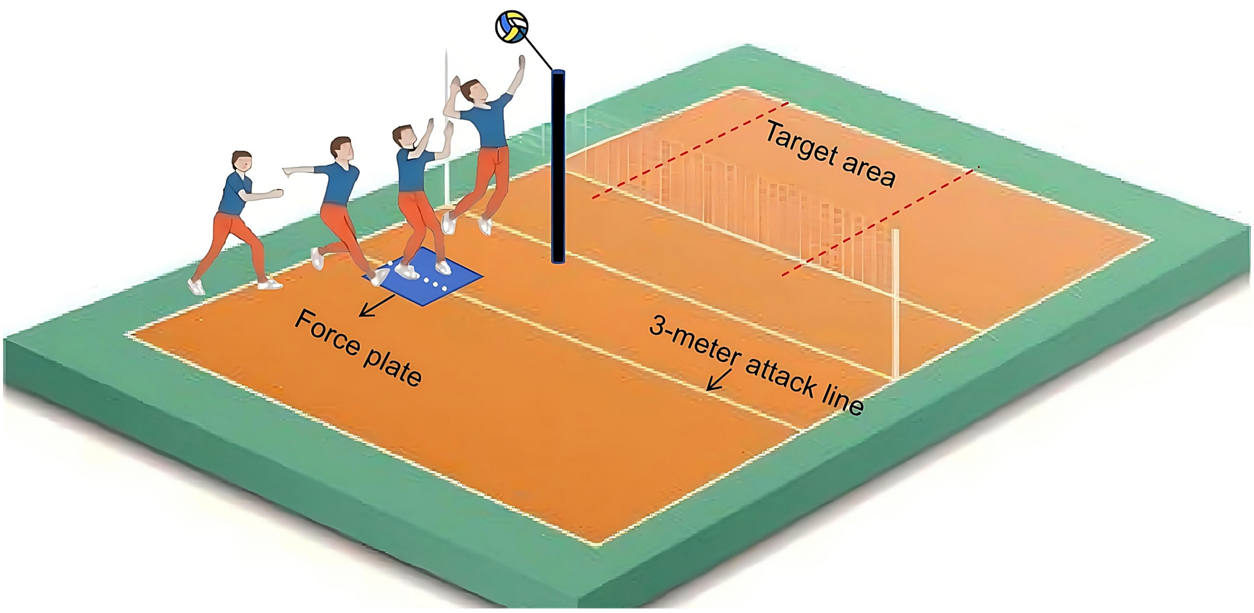

FIGURE 1. Experimental site setting. Schematic setup of the SPJ test on a standard volleyball court. Athletes performed an approach and spike over the net, stepping on a force plate placed on the attack path close to the 3-m attack line to record the ground-reaction forces during the plant and take-off. Successful trials were required to land in the predefined target area.

After a standardized warm-up, athletes performed familiarization trials under investigator supervision until they were comfortable with the task. They were permitted to choose their preferred approach distance and angle and to adopt a self-selected starting position.

Each participant was required to perform five valid SPJ. Their goal was to maximize jump height and to strike the suspended ball into a designated target area on the opposite court. A trial was considered valid if both feet contacted the two separate force plates during take-off and the ball was hit into the target area. Trials were deemed invalid if the net was touched, as this could affect jump performance or was considered a rule violation.

A 1-min rest interval was provided between trials to minimize fatigue, and participants were instructed to perform approach jumps that replicated typical match conditions.

2.3 Data collection

A 13-camera infrared motion capture system (Prime17w, OptiTrack, NaturalPoint Inc., Corvallis, OR, USA) recorded the trajectories of 57 retroreflective markers (14 mm diameter) at 240 Hz. Marker placement followed previously described protocols [19]. Two AMTI force platforms (OR6-6-2000, AMTI Inc., Watertown, MA, USA) simultaneously recorded ground reaction forces at 1200 Hz. Kinematic and kinetic data were synchronized in Motive 2.2.0 (OptiTrack, NaturalPoint Inc., Corvallis, OR, USA).

2.4 Data processing

Kinematic and kinetic data were processed in Visual3D x64 v2024.10.4 (C-Motion, Inc., Rockville, MD, USA) using a 15-segment skeletal model (feet, shanks, thighs, pelvis, trunk, head, upper arms, forearms, hands). Joint centers were defined using bilateral reflective markers. Hip joint centers were estimated in Visual3D using its built-in Cartesian Optoelectronic Dynamic Anthropometer (CODA) pelvis model (Charnwood Dynamics Ltd., Leicestershire, UK), which uses regression-based equations to compute hip joint center locations, *i.e.*, hip joint locations. The phases of the SPJs were defined using combined kinematic and kinetic criteria, consistent with previous work, and are illustrated in (Fig. 2, Ref. [9]) [10].

Net joint torques and reaction forces for the lower extremities were computed via inverse dynamics. Marker trajectories and ground reaction forces were filtered using a fourth-order zero-lag Butterworth filter (6 Hz for kinematics [21], 20 Hz for kinetics [22]). Energy flow was analyzed following Robertson and Winter [23] using two variables: joint force power (JFP) and joint torque power (JTP). JFP represents energy transfer between adjacent segments, where a positive value indicates energy inflow and a negative value indicates energy outflow (Eqn. 1):

$$JFP = \vec{F}_{ij} \cdot \vec{V}_j \tag{1}$$

JTP represents energy generation, absorption, or transfer via joint torques: $JTP = STP_{proximal} + STP_{distal}$ where $STP = \vec{T}_{ij} \cdot \vec{\omega_j}$.

When the proximal and distal STPs have the same sign

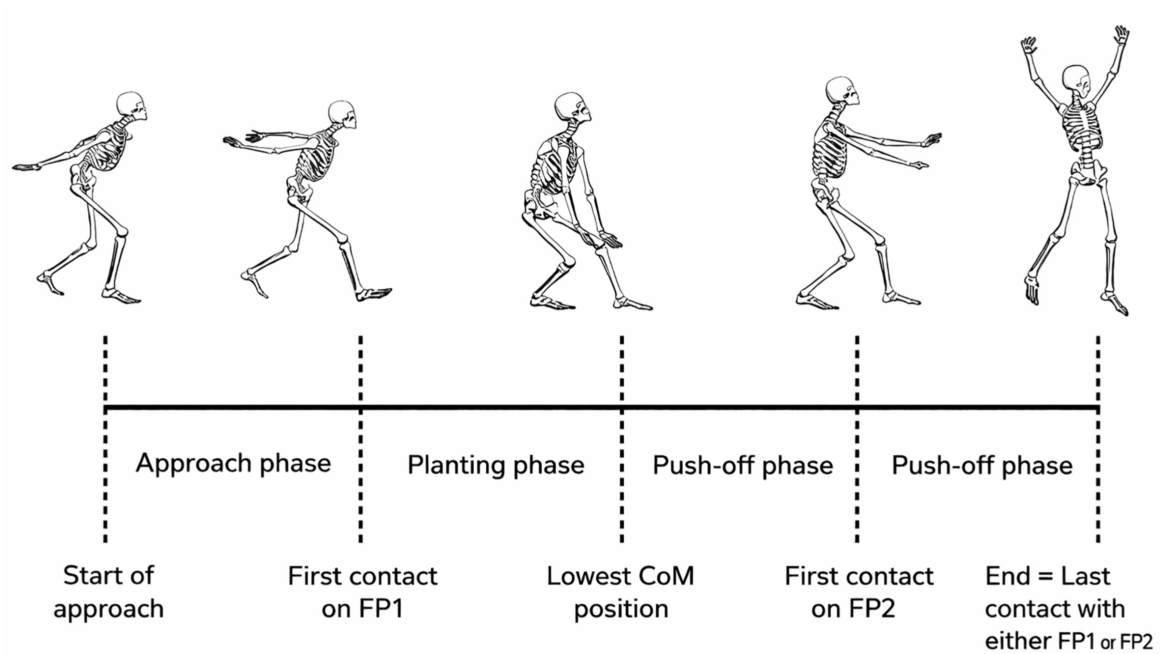

FIGURE 2. Phases of the SPJs. Approach phase: from the start of the approach to the first ground contact of the dominant foot. Planting phase: from the end of the approach phase to the instant of the lowest CoM. Push-off phase: from the end of the planting phase to the last ground contact at take-off; this interval includes the ground contact of the non-dominant foot. Take-off: the final contact with either force plate (FP1 or FP2), identified using a 20 N [9] ground reaction force threshold. FP: force plate; CoM: center of mass.

(or one is zero), JTP is interpreted as net energy generation (positive) or absorption (negative) at that joint. In the present study, JTP was analyzed in this sense as joint-level energy generation rather than decomposed into a separate "torque-mediated transfer" term. The transfer component of JTP has been reported to contribute minimally during explosive jump tasks and was not examined independently here [18].

For each leg, JFP and JTP were integrated over the take-off phase, defined from the instant when whole-body CoM vertical velocity reached zero to the instant when ground reaction force (GRF) on the force plate dropped below 20 N [9]. The resulting integrals were interpreted as total transferred energy (from JFP) and total generated energy (from positive JTP) for that phase.

To compare inter-limb strategy, the percentage contribution of each joint (hip, knee, ankle) to total transferred energy and to total generated energy was calculated. All instantaneous power terms (JFP, JTP) and their time integrals were normalized to body mass (W/kg for power, J/kg for work-like integrals).

2.5 Statistical analysis

Descriptive statistics (mean ± standard deviation (SD)) were calculated for all variables. Normality was assessed with the Shapiro-Wilk test, and all variables met the normality assumption ($p > 0.05$). Accordingly, two-tailed paired-samples *t*-tests were used for all limb comparisons with $\alpha = 0.05$.

Effect sizes for paired comparisons were reported as Cohen's $d = t/\sqrt{n}$ (based on the SD of the paired differences). The sign convention was DL-N-DL; therefore, negative Cohen's d values indicate higher means in the non-dominant leg. Ninety-five percent confidence intervals (95% CI) for Cohen's d were obtained from the noncentral t distribution.

A sensitivity power analysis for the paired-samples *t*-test ($\alpha = 0.05$, two-tailed; power = 0.80; N = 11) was performed in G*Power (version 3.1.9.7; Universität Kiel, Kiel, SH, Germany), indicating that the design could detect paired differences of approximately $d \geq 0.94$ [24]. Most between-limb effects met or exceeded this magnitude. The knee-joint work difference during energy generation showed a slightly smaller effect ($d = 0.92$) but remained statistically significant ($p = 0.013$) and large in practical terms, indicating that this asymmetry is likely meaningful despite marginally lower a priori power.

All statistical analyses were performed in IBM SPSS Statistics, version 27 (IBM Corp., Armonk, NY, USA). p-values are reported to three decimals ($p < 0.001$ where appropriate); units are given in the corresponding tables.

3. Results

3.1 Approach velocity and jump height

The mean jump height based on CoM displacement was 0.65 ± 0.06 m, and the approach velocity was 3.66 ± 0.25 m/s, which is comparable to previously reported values in elite male volleyball players performing SPJs (0.67 ± 0.07 m; 3.71 ± 0.33 m/s) [7].

3.2 Energy generation differences between legs

The DL produced significantly greater total mechanical work than the N-DL ($p = 0.002$; $d = 1.27$, very large). Knee ($p = 0.013$; $d = 0.92$, large) and ankle joint work ($p = 0.003$; $d = 1.18$, large) were significantly higher in the DL, whereas hip work showed no significant difference ($p = 0.335$; $d = 0.31$, small).

Hip peak power was significantly higher in the N-DL ($p < 0.001$; $d = -2.22$, extremely large), while knee ($p = 0.903$; $d = 0.04$, trivial) and ankle ($p = 0.250$; $d = 0.37$, small) peak power showed no significant differences.

Joint contribution percentages did not differ significantly across the legs for hip ($p = 0.568$; $d = -0.18$, small), knee ($p = 0.839$; $d = 0.06$, trivial), or ankle ($p = 0.556$; $d = 0.18$, small) (Table 1).

Interpretation: The DL greater total mechanical work, concentrated at the knee and ankle, indicates higher cumulative extensor demand during take-off. Repeated exposure to such propulsive demands may increase mechanical loading associated with patellar tendon stress and Achilles tendon overload.

3.3 Energy transfer differences between legs

The N-DL transferred significantly more total energy than the DL ($p = 0.005$; $d = -1.08$, large). Joint-specific analysis showed greater energy transfer in the N-DL at the hip ($p = 0.006$; $d = -1.04$, large), knee ($p = 0.009$; $d = -0.97$, large), and ankle ($p = 0.006$; $d = -1.04$, large).

Peak transfer power was also significantly higher in the N-DL at the hip ($p < 0.001$; $d = -1.71$, very large), knee ($p = 0.008$; $d = -1.00$, large), and ankle ($p = 0.008$; $d = -0.99$, large).

Joint contribution percentages (%) did not differ significantly between legs for the hip ($p = 0.423$; $d = -0.25$, small), knee ($p = 0.465$; $d = 0.23$, small), or ankle ($p = 0.900$; $d = 0.04$, trivial) (Table 2).

Interpretation: The N-DL's role as the primary conduit for horizontal-to-vertical energy transfer places it under greater deceleration and frontal-plane control demands. This loading pattern is consistent with mechanisms of lateral ankle sprain and ACL strain, particularly when rapid approach speed or unanticipated opponent contact challenges neuromuscular control. The high peak transfer power at the hip further highlights the need for strong gluteal and trunk stabilizer function to limit knee valgus and protect the ACL during explosive take-offs.

4. Discussion

The present findings demonstrate significant inter-limb differences in energy generation and transfer during the take-off phase of the SPJs, consistent with prior work [7, 10]. Despite these asymmetries in magnitude, both legs followed a similar pattern of energy utilization (Fig. 3, Ref. [9]). This suggests that inter-limb coordination in the SPJs is not random or imbalanced but instead reflects task-specific specialization: one limb primarily redirects approach momentum, and the other primarily generates vertical propulsion. This pattern may

TABLE 1. Peak power and joint contributions for energy generation.

Variable	Dominant leg (mean ± SD)	Non-dominant leg (mean ± SD)	p	Cohen's d	95% CI (d)
Peak power (W/kg)					
Hip joint	10.15 ± 1.91	22.52 ± 5.34	<0.001	−2.22	(3.34, −1.08)
Knee joint	26.14 ± 4.16	25.98 ± 4.11	0.903	0.04	(−0.56, 0.63)
Ankle joint	17.69 ± 2.53	16.29 ± 2.31	0.250	0.37	(−0.25, 0.97)
Joint work (J/kg)					
Hip joint	1.21 ± 0.21	1.09 ± 0.44	0.335	0.31	(−0.31, 0.90)
Knee joint	1.74 ± 0.20	1.42 ± 0.33	0.013	0.92	(0.19, 1.61)
Ankle joint	1.28 ± 0.09	1.03 ± 0.18	0.003	1.18	(0.38, 1.94)
Total work	4.23 ± 0.28	3.55 ± 0.64	0.002	1.27	(0.45, 2.06)
Joint Contribution (%)					
Hip joint	28.64 ± 4.28	29.99 ± 8.16	0.568	−0.18	(−0.77, 0.42)
Knee joint	41.11 ± 3.61	40.52 ± 8.67	0.839	0.06	(−0.53, 0.63)
Ankle joint	30.25 ± 2.32	29.49 ± 3.96	0.556	0.18	(−0.42, 0.78)

Values are mean ± SD and normalized to body mass (W/kg for peak power; J/kg for work). Cohen's d is calculated from paired differences (DL-N-DL); negative values indicate greater values in the non-dominant leg (N-DL). 95% CI reflects the confidence interval for Cohen's d. SD: standard deviation; CI: confidence interval.

TABLE 2. Peak power and joint contributions for energy transfer.

Variable	Dominant leg (mean ± SD)	Non-dominant leg (mean ± SD)	p	Cohen's d	95% CI (d)
Peak power (W/kg)					
Hip joint	26.04 ± 3.27	31.58 ± 4.85	<0.001	−1.71	(−2.64, −0.75)
Knee joint	23.75 ± 4.20	30.26 ± 4.27	0.008	−1.00	(−1.71, −0.25)
Ankle joint	19.41 ± 2.42	27.43 ± 4.16	0.008	−0.99	(−1.71, −0.25)
Joint work (J/kg)					
Hip joint	2.08 ± 0.28	2.69 ± 0.47	0.006	−1.04	(−1.76, −0.28)
Knee joint	1.61 ± 0.22	2.03 ± 0.43	0.009	−0.97	(−1.68, −0.23)
Ankle joint	1.55 ± 0.28	1.95 ± 0.37	0.006	−1.04	(−1.77, −0.28)
Total work	5.24 ± 0.73	6.67 ± 1.19	0.005	−1.08	(−1.82, −0.31)
Joint Contribution (%)					
Hip joint	39.80 ± 1.81	40.48 ± 2.56	0.423	−0.25	(−0.85, 0.36)
Knee joint	30.83 ± 1.78	30.25 ± 1.54	0.465	0.23	(−0.38, 0.82)
Ankle joint	29.37 ± 2.13	29.27 ± 2.04	0.900	0.04	(−0.55, 0.63)

Values are mean ± SD and normalized to body mass (W/kg for peak power; J/kg for work). Cohen's d is calculated from paired differences (DL-N-DL); negative values indicate greater values in the non-dominant leg (N-DL). 95% CI reflects the confidence interval for Cohen's d. SD: standard deviation; CI: confidence interval.

support whole-body stability and performance while distributing mechanical load across different tissues rather than relying on a single limb.

4.1 Energy generation

The DL produced significantly more total energy during take-off (p = 0.002, d = 1.27), driven by an earlier onset and longer duration of power generation (Fig. 3). Because the CoM is positioned closer to the DL at plant, this leg must initiate and sustain vertical acceleration for longer [7, 25]. This concentrates high-magnitude loading on the knee extensors and ankle plantarflexors of the DL, increasing mechanical demand on the quadriceps patellar tendon complex and the triceps surae Achilles tendon complex [9, 17]. Repetition of this high extensor output across many spikes may increase exposure to mechanical conditions associated with patellar tendon stress and Achilles overuse [26, 27].

Interestingly, although the DL hip began producing energy before the CoM reached its lowest point, its peak power was lower than that of the N-DL ($p < 0.001$, $d = -2.22$). This likely reflects coordination rather than weakness. First, arm swing

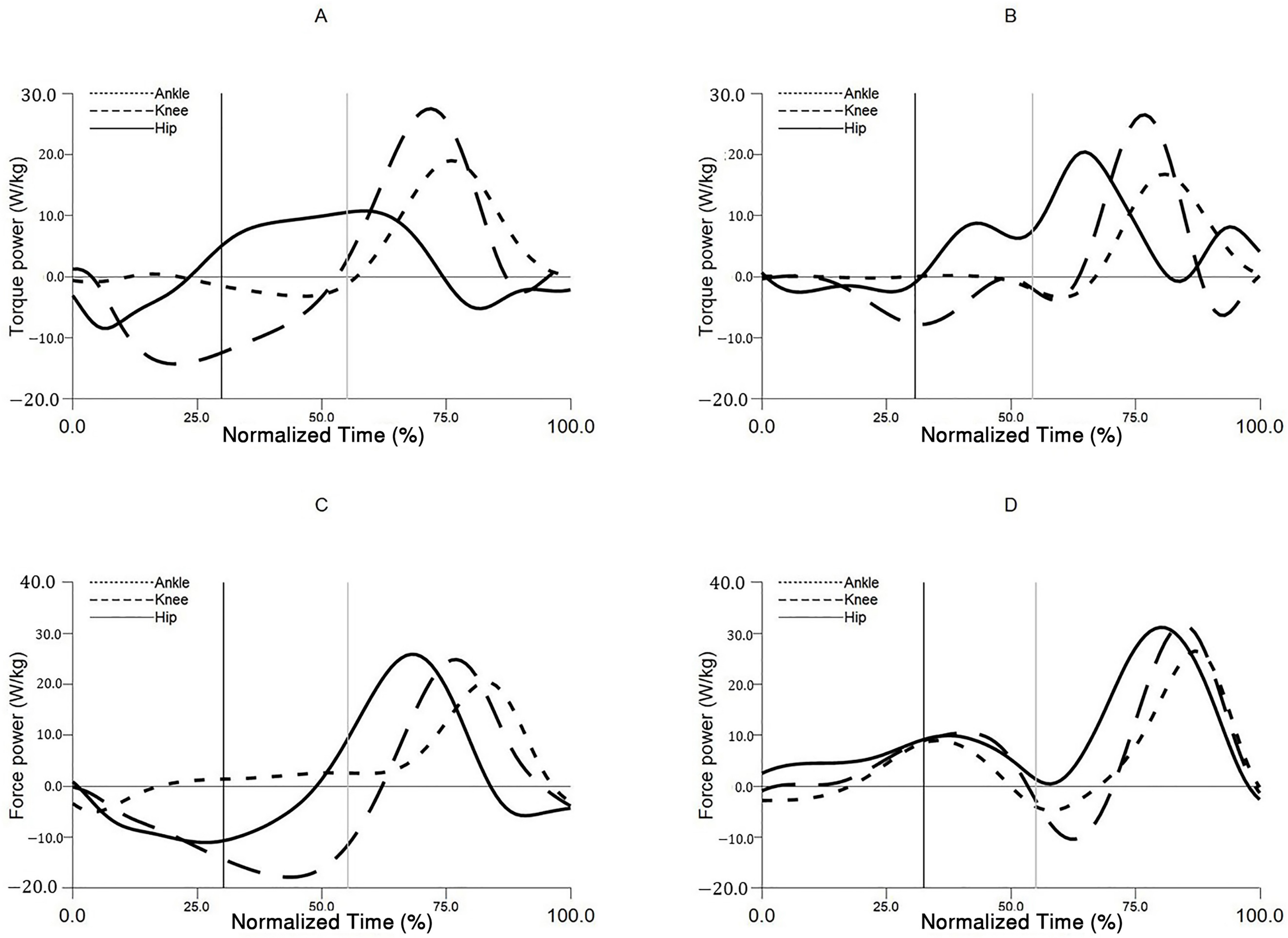

FIGURE 3. Joint torque power (W/kg) and joint force power (W/kg) at the hip, knee, and ankle joints of the DL and N-DL during the take-off phase of the SPJs. Time-normalized joint power during the SPJs (0–100% from planting onset to final ground contact; events detected with a 20 N GRF threshold). A: DL JTP. B: N-DL JTP. C: DL JFP. D: N-DL JFP. Vertical black line = lowest CoM; vertical gray line = N-DL foot contact (FP2 >20 N) [9]. Line styles denote ankle, knee, and hip. For clarity, only the energy transferred proximally at each joint is shown (*e.g.*, the energy transferred to the thigh segment is used to represent the knee joint). All power values were normalized to body mass (W/kg).

and trunk inclination can prolong hip extension while simultaneously increasing anterior trunk momentum [28, 29]; if poorly controlled, this may elevate lumbar and hip joint stress even as it improves jump height [30]. Second, when the DL knee extensors are producing large concentric torque, the rectus femoris must generate high force. Because the rectus femoris spans both the hip and knee, its high activation contributes a flexor moment at the hip, which effectively opposes the net hip extensor moment generated by the gluteal and hamstring muscles [31]. At the same time, large quadriceps forces acting in a flexed-knee posture increase patellofemoral joint reaction force due to a high compressive load on the patellofemoral joint [32]. In addition, when the knee is flexed, the hamstrings are mechanically disadvantaged: they are shortened over the knee and thus less able to generate hip extension torque or to resist anterior tibial translation, which places greater anterior shear demand on the ACL [33–35]. Taken together, these interactions suggest that the DL's role in propulsion is achieved primarily through knee- and ankle-dominant output, rather than through maximal instantaneous hip power.

4.2 Energy transfer

The N-DL exhibited significantly greater total energy transfer than the DL (p = 0.005; d = −1.08), indicating that it functions primarily as the braking and redirection limb during the initial take-off phase. The N-DL manages the conversion of approach-run horizontal momentum into vertical motion, generating a large horizontal impulse and decelerating the body, while controlling frontal-plane motion [10, 25]. This exposes the N-DL to high multiplanar loads, including valgus and rotational moments at the knee and inversion stresses at the ankle, all of which are consistent with established mechanisms for non-contact ACL injury, patellofemoral overload, and lateral ankle sprain—especially under fatigue or perturbation [36–39].

In double-leg SPJs, this redistribution of braking demand to the N-DL appears to permit the DL to focus on vertical propulsion. In contrast, during single-leg SPJs, the plant leg must both brake and propel, which is associated with higher horizontal ground reaction forces and less efficient conversion of horizontal to vertical impulse [9, 40]. The current findings, therefore, suggest that in the bilateral SPJs, the N-DL serves as the primary braking limb that stabilizes and reorients the system, while the DL capitalizes on that stability to generate lift. Functionally, this means the N-DL accumulates repeated high deceleration loads similar to single-leg tasks, which may increase exposure to conditions linked to ankle instability and ACL strain over time.

4.3 Task-specific specialization

Although the DL and N-DL differed in the total energy generated and transferred, they showed almost identical hip, knee, ankle contribution ratios and followed the same proximal-to-distal coordination sequence [41, 42]. This indicates that the two limbs do not use fundamentally different motor patterns; instead, the same coordination template is expressed for different functional roles; the N-DL brakes and redirects horizontal momentum, and the DL drives vertical propulsion [7, 10, 25].

In this pattern, the DL is the limb that produces more total mechanical energy and sustains this output for longer, which is consistent with a predominantly propulsive task. By contrast, the N-DL shows greater inter-joint energy transfer and more evident multiplanar involvement, indicating that it is the limb that handles the redirection of the approach momentum and the control of body alignment during take-off, rather than simply "pushing" vertically.

Because these roles expose the two limbs to different dominant loading conditions, training should mirror the limb-specific demands rather than force artificial symmetry. For the DL, repeated high knee- and ankle-extensor output warrants (i) eccentric quadriceps and triceps-surae strengthening and (ii) exercises that maintain hip contribution to propulsion, to avoid a purely knee-dominant pattern that may increase patellofemoral or patellar tendon loading. For the N-DL, drills that emphasize single-leg balance in the frontal plane, hip-abductor/external-rotator strength, and controlled redirection of approach velocity are appropriate, because they directly target the multiplanar energy-transfer role identified in this limb.

These training directions should be interpreted as load-management suggestions derived from the observed energy-generation and energy-transfer patterns, not as injury prediction. Prospective and fatigue-modeling studies are still required to establish dose-response relationships between limb-specific loading and actual injury occurrence.

4.4 Limitations

This study inferred limb-specific mechanical loading exposure from biomechanical variables obtained during the SPJ, rather than from prospectively observed injury incidence. We did not collect longitudinal or prospective injury data, so we cannot claim that the identified loading profiles cause or predict injury; rather, they should be interpreted as indicating exposure to mechanical conditions that have been associated with patellar tendon stress, patellofemoral overload, ACL-related valgus and rotational loading, and lateral ankle sprain/instability in previous reports.

The sample consisted of 11 elite male collegiate volleyball athletes, which improves ecological validity for competitive play but limits generalizability and raises the possibility that some very large effect sizes were inflated by individual variability.

Future studies should incorporate subject-specific musculoskeletal modeling and data-driven ligament-fatigue analyses to evaluate how repeated exposure to these loading conditions may contribute to progressive tissue-level vulnerability over time [43].

5. Conclusions

This study identified distinct yet complementary roles of the DL and N-DL during the take-off phase of the SPJ. The DL primarily acts as the propulsive limb, generating vertical impulse through repeated knee-extensor and ankle-plantarflexor demand, which may increase exposure to mechanical loading patterns associated with patellar tendinopathy and Achilles tendon overload. The N-DL functions as the braking-and-redirection limb, handling multiplanar demands and frontal-plane control during take-off, which may increase exposure to ACL-related knee loading and lateral ankle sprain mechanisms. These task-specific loading profiles suggest that limb-specific neuromuscular conditioning and technical coaching may be more appropriate for managing SPJ mechanical demands than approaches that assume bilateral symmetry.

From a practical perspective, these results emphasize that performance and load management in the SPJ should be considered bilaterally and within the context of the whole approach- plant- take-off sequence, rather than in terms of isolated single-limb strength. Training strategies that enhance inter-limb timing, refine the planting strategy, and improve the efficiency of horizontal-to-vertical momentum redirection may help athletes generate vertical impulse more effectively while better managing limb-specific mechanical loading exposure. Future work should extend the analysis beyond the final take-off phase to include the entire approach sequence, and examine how variations in CoM trajectory, approach speed, and planting strategy modify each limb's contribution to energy generation and transfer.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

HYY, BYS and SK—designed the research study. HYY, SW, BYS and ZXZ—performed the research. BYS and SK—provided help and advice on design, experimental set-up, interpretation, and resources. HYY, ZXZ and SW—analyzed the data. HYY, SK and BS—wrote and revise the manuscript. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

This study complied with the Declaration of Helsinki. The study protocol was explained to all participants, and written informed consent was obtained from each of them. The protocol was approved by the Institutional Review Board of Jeonbuk National University (JBNU2024-09-015-002) and the study was performed in accordance with all relevant guidelines and regulations.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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