



Statistical Parametric Mapping-Based Comparison of Lower-Limb Biomechanics Between Two Drop Jump Strategies

Pang Haoze^{a†}, Zhao Rui^{a†}, Lee Seongno^{a,b}, & Siddhartha Bikram Panday^{a,b,c*}

^aDepartment of Physical Education, Hanyang University, Seoul, Republic of Korea

^bDivision of Sports Industry and Science, Hanyang University, Seoul, Republic of Korea

^cDepartment of Art and Sportainment, Hanyang University, Seoul, South Korea

[†]Pang Haoze and Zhao Rui Contributed Equally to This Work and Share First Authorship

Abstract

This study compared the kinematic and kinetic time-series characteristics of the lower-limb joints between bounce drop jumps (BDJ) and countermovement drop jumps (CDJ) to clarify differences in energy absorption and control mechanisms. Twenty male participants performed BDJ and CDJ under identical relative loading conditions based on individual countermovement jump height. Kinematic and kinetic data of the ankle, knee, and hip joints were collected using a motion capture system and force plates, and joint angular velocity, moment, and power were calculated via inverse dynamics. Statistical Parametric Mapping (SPM) *t*-tests were applied across the entire ground-contact phase. The analysis revealed that joint-angle differences between BDJ and CDJ were primarily driven by the hip and knee across all three planes, whereas the ankle showed only brief and relatively small angular differences but consistently higher angular velocities in BDJ. Angular-velocity patterns indicated a distal-to-proximal redistribution strategy, with BDJ exhibiting earlier and more frequent dominance at the ankle and CDJ showing broader and more sustained dominance at the hip and knee. Kinetic differences were mainly observed in the sagittal plane: CDJ demonstrated larger and longer-lasting joint moments across all joints, reflecting greater eccentric control, while joint-power differences were confined to short, phase-specific intervals, indicating distinct energy-distribution strategies despite comparable overall output. These findings suggest that BDJ emphasizes rapid elastic utilization at the distal joints, whereas CDJ relies more on active proximal force generation. Accordingly, BDJ may be preferable for explosive rebound tasks, whereas CDJ may be more suitable for controlled force production. These findings further demonstrate the value of SPM for identifying phase-specific biomechanical differences.

Key words: drop jump, Bounce drop jump (BDJ), countermovement drop jump (CDJ), lower limb biomechanics, Statistical Parametric Mapping (SPM), plyometric training

Introduction

The drop jump is a classic form of plyometric training designed to enhance lower-limb explosive power. Its core principle lies in the stretch-shortening

cycle (SSC), which enables rapid energy conversion and quick mechanical response during movement (Ciocca et al., 2021; Makaruk et al., 2012). In actual training settings, the execution strategy of the drop jump (Matic et al., 2015) is not uniform. Two representative technical variations are the bounce drop jump (BDJ) and the countermovement drop jump (CDJ) (Marshall & Moran, 2013). The BDJ generally features a shorter ground contact time and smaller flexion-extension

Submitted : 27 February 2026

Revised : 2 May 2026

Accepted : 8 June 2026

* Correspondence : siddhartha@hanyang.ac.kr

angular displacement, reflecting a more condensed temporal structure and a rapid external mechanical response. In contrast, the CDJ involves a longer cushioning phase and deeper countermovement, resulting in a distinct phase structure and energy transfer pathway (Bobbert et al., 1987). These differences correspond to distinct motor control strategies and kinematic–kinetic configurations; however, a systematic comparison under consistent task constraints and measurement frameworks is still required to clearly identify their specific characteristics.

Previous studies comparing drop jump techniques have primarily relied on discrete time points—such as peak values or specific reference frames—for statistical testing (Bobbert et al., 1987; Marshall & Moran, 2013; Struzik et al., 2016; Walsh et al., 2004). While this approach is useful for quickly extracting representative indicators, it struggles to preserve the continuous structure of time-series signals, and the results can be heavily influenced by the subjective selection of time points. Statistical Parametric Mapping (SPM), based on Random Field Theory, enables statistical inference across the entire time domain, allowing for the direct identification of specific time intervals where differences occur while preserving the sequential information of the waveform (Duan et al., 2025). For dynamic tasks like the drop jump—characterized by a condensed temporal structure and rapid phase transitions, applying SPM as a primary analytical framework helps prevent information loss that occurs when focusing solely on peak values while overlooking the underlying process. This approach enhances temporal resolution and interpretive power when describing strategic differences in movement patterns.

According to training theory, the extent to which a specific exercise enhances sport-specific performance depends on the biomechanical and kinematic similarity between the training movement and the actual sport movement (Zatsiorsky, 1995). Identifying the differences between BDJ and CDJ in the time-series patterns and energy distribution of the lower-limb joints not only deepens the understanding of these two drop jump techniques but also provides coaches and athletes with a scientific basis for selecting the most suitable

technique according to sport-specific demands. This, in turn, can enhance training effectiveness and transferability of performance gains. Moreover, because drop-jump tasks involve rapid landing–take-off transitions and substantial lower-limb loading, clarifying the joint-specific mechanical demands of different execution strategies may also help coaches select and prescribe these exercises more appropriately within plyometric training.

In addition, many previous studies have conducted drop jump tests using an absolute drop height (Bobbert et al., 1987; Marshall & Moran, 2013; Martinez, 2016; Struzik et al., 2016; Young et al., 1995). Without accounting for individual differences in jumping ability or body size, some participants may experience excessive impact beyond their capacity, while others may receive insufficient training stimuli (Peng et al., 2017). In particular, when there are large differences in physical condition, a fixed drop height can lead to biomechanically different actual falling distances, which may in turn affect the level of lower limb loading and the expression of motor control strategies.

Some studies have suggested setting a relative drop height—for example, a certain percentage of each participant’s maximum countermovement jump (CMJ)—in drop jump tests to control the level of mechanical challenge experienced by each individual (Matic et al., 2015). A consistent relative intensity helps eliminate the influence of individual differences in ability and body size on jump strategy and energy distribution, thereby enhancing the validity of between-group comparisons and strengthening the generalizability of the research findings.

In this study, the SPM was applied to compare the angular velocity, joint torque, and power curves of the ankle, knee, and hip throughout the entire landing contact phase, as participants performed two drop jump strategies—BDJ and CDJ—under an identical relative loading condition (drop height based on each individual’s CMJ height). Through this analysis, the study aimed to identify the kinematic and kinetic differences and the characteristics of energy control mechanisms between the two strategies, providing insights for training applications and injury prevention.

Methods

Participants

Twenty male participants with prior athletic training experience and no history of lower-limb injury were recruited for this experiment. Their basic characteristics were as follows: age 23 ± 1.58 years, body mass 65 ± 3.71 kg, and height 1.78 ± 0.067 m. None of the participants had engaged in high-intensity exercise within 24 hours before testing, had sustained a lower-limb injury during the previous six months, or reported any health condition that could affect performance. All participants were informed of the experimental procedures and potential risks before testing and voluntarily participated in the experiment.

Equipment

Three-dimensional kinematic data were collected using a Vicon optical motion capture system equipped with eight T40S infrared cameras (Vicon Motion Systems Ltd., Oxford, UK). Marker trajectories were recorded at a sampling frequency of 100 Hz. Ground reaction forces were synchronously measured using embedded force platforms (AMTI Gen-5; Advanced Mechanical Technology, Inc., USA) at a sampling frequency of 1500 Hz. Kinematic and kinetic data were temporally synchronized through the Vicon data acquisition system.

A full-body Plug-in Gait marker set was used for biomechanical modeling. A total of 39 reflective markers were attached to the following anatomical landmarks and segment locations: LFHD, RFHD, LBHD, and RBHD on the head; C7, T10, CLAV, STRN, and RBAK on the trunk; LSHO, LUPA, LELB, LFRM, LWRA, LWRB, and LFIN on the left upper limb; RSHO, RUPA, RELB, RFRM, RWRA, RWRB, and RFIN on the right upper limb; LASI, RASI, LPSI, and RPSI on the pelvis; LTHI, LKNE, LTIB, LANK, LHEE, and LTOE on the left lower limb; and RTHI, RKNE, RTIB, RANK, RHEE, and RTOE on the right lower limb. This marker configuration was used to define the trunk, pelvis, thigh, shank, and foot segments

and to calculate lower-limb joint kinematics and kinetics through inverse dynamics.

Procedure

Pre-experimental Preparation and Standardized Warm-up

All participants performed a 15-minute standardized warm-up prior to measurement, which included aerobic running, dynamic stretching, core and lower-limb isometric activation, and practice trials of BDJ and CDJ movements. Following the warm-up, each participant's basic anthropometric data (e.g., height, body mass, limb length, and joint width) was recorded. Reflective markers were then attached to key bony landmarks on the trunk and upper and lower limbs by the researcher. Participants adopted a standard static standing posture, which was used to calibrate the model for subsequent kinematic modeling.

Standardization of Drop Jump Height

Participants stood naturally at the center of the force platform with both hands placed on their hips and performed a rapid downward-upward countermovement without any preliminary pause (Figure 1). A trial was considered valid when both feet landed simultaneously and the participant maintained a stable upright posture for 1–2 seconds after landing. A 30-second rest interval was provided between trials, and each participant completed three valid CMJ attempts. The actual CMJ height was calculated as the difference between the maximum center of mass (COM) height attained during the jump and the mean COM height over 10 consecutive frames during a stable static standing posture (Dos' Santos et al., 2018). The calculated jump height for each trial was rounded to the nearest whole centimeter, and the highest value obtained from the three valid trials was designated as the participant's 100% CMJ height.

Subsequently, an adjustable-height platform was set according to each participant's individual CMJ-based reference height, which served as the starting point for



Figure 1. Experimental setup and device for setting the starting height of the drop jump

the drop jump tasks. This setup ensured that all participants performed the BDJ and CDJ tasks under a uniform relative mechanical challenge level, allowing for controlled comparison across individuals.

Drop Jump Tasks

BDJ: With both hands placed on the hips, participants positioned their feet at the edge of the platform and leaned the body slightly forward, extending the dominant leg first to initiate a natural

descent without any initial push-off (Figure 2). Upon simultaneous landing with both feet at the center of the force platform, participants were instructed to minimize ground contact time and immediately perform a vertical rebound jump. After the jump, they were required to land stably and maintain postural balance to complete a valid trial (Bobbert et al., 1987).

CDJ: The initial procedure was identical to that of the BDJ. However, after landing, participants performed a larger countermovement involving greater downward flexion and extension, aiming to achieve the highest possible vertical jump. As in the BDJ, participants were required to land stably and maintain postural balance upon completion of the movement to ensure a valid trial (Bobbert et al., 1987).

To ensure movement quality and measurement consistency, the researcher verbally emphasized the key technical points of the two drop jump techniques and provided a demonstration before testing. Each participant then performed 1–2 non-recorded practice jumps to familiarize themselves with the procedures and technical requirements. Participants first performed the BDJ trials followed by the CDJ trials, both from

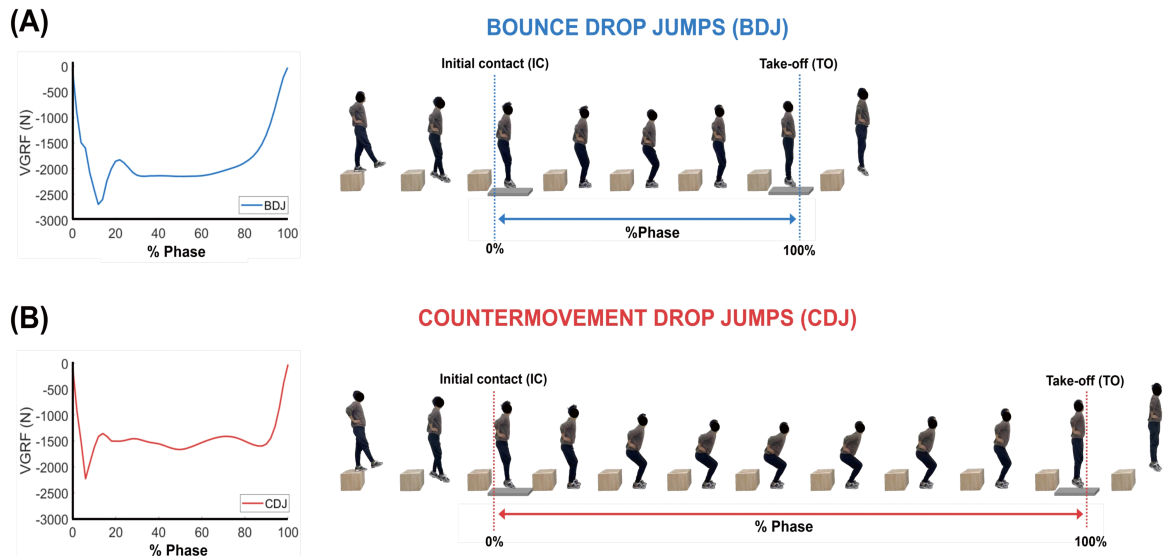


Figure 2. Comparison of bounce drop jumps (BDJ) and countermovement drop jumps (CDJ). Left panels depict time-normalized vertical ground reaction force (VGRF) profiles plotted as a function of percentage phase (%Phase), from initial ground contact (0%) to take-off (100%). Right panels show representative movement sequences illustrating the distinct motor strategies of each task, with dashed vertical lines indicating the start and end of the analyzed ground-contact interval.

the 100% CMJ-based drop height. A 30-second rest interval was provided between repeated trials of the same movement, and a 4–5 minutes rest interval was given between the BDJ and CDJ conditions. Each participant completed three valid trials of both BDJ and CDJ. A trial was considered valid if (1) both feet landed fully on the force platform, and (2) the movement conformed to the specific execution requirements of the BDJ or CDJ, respectively.

Data Processing

In this study, data from each participant's dominant lower limb was selected for kinematic and kinetic calculations. The collected three-dimensional kinematic data and ground reaction force data were exported via Vicon Nexus 2.12.1 and imported into Visual3D (v3.26, C-Motion Inc., Germantown, MD, USA) for recognition and modeling.

After constructing an individualized biomechanical model for each participant, an inverse dynamics approach was applied to calculate the joint angle, angular velocity, moment, and power of the ankle, knee, and hip. All kinematic and kinetic data were smoothed using a fourth-order zero-lag Butterworth low-pass filter with a cutoff frequency of 6 Hz to remove high-frequency noise.

Subsequently, all one-dimensional continuous data were exported to MATLAB R2024a (The MathWorks, MA, USA), where data processing procedures such as normalization were performed using a custom MATLAB script developed for this study.

Because BDJ and CDJ differ in their movement control rhythms, key events such as the initial landing absorption, the transition from negative to positive work, and the final propulsion phase do not occupy exactly the same proportions along the normalized time axis. Therefore, when directly compared on a unified timeline, functionally equivalent phases may not align precisely.

In this study, an event anchoring procedure was implemented, conceptually derived from the piecewise linear length normalization (PLLN) method proposed by Helwig (Helwig et al., 2011). In PLLN, time-series

trajectories are segmented into subphases using points of interest, and these points may be defined according to trajectory-shape characteristics or kinematically relevant events.

After phase normalization, each trial's time series was reparameterized based on key biomechanical events to enable comparisons across functionally equivalent phases. Unlike conventional normalization, this approach aligns trajectories at meaningful events while simultaneously preserving the natural rhythm differences inherent to the two movement strategies.

Anchor Points and Functional Meaning:

To encompass the major functional transitions within the contact phase, three anchor points were established, dividing the contact phase into four stages (Figure 3). The three anchor points were defined using a combination of previously used biomechanical events and data-driven interpretation of the present drop-jump curves. The absorption peak was selected because vertical ground reaction force is an important indicator of external loading during drop-jump tasks, and peak force and force-development characteristics are commonly used to describe impact loading and shock absorption during force-plate assessments (Ortega et al., 2010). Peak knee flexion was selected because previous drop-jump studies have commonly used the instant of maximum knee flexion to separate the braking/eccentric phase from the push-off or concentric phase (Lazaridis et al., 2013; Ruschel et al., 2016; Bassa et al., 2023). However, using only the absorption peak and peak knee flexion would mainly align the early landing absorption and eccentric braking portions of the movement, while providing limited temporal alignment for the later concentric propulsion phase. Therefore, the propulsion inflection point was introduced as an additional late-contact anchor. This point was not treated as a predefined event directly adopted from previous studies; instead, it was identified using the Kneedle algorithm as a data-driven reference point on the VGRF curve to represent the transition toward rapid propulsive force development.

- ① Absorption Peak: Defined as the first significant local peak of the vertical ground reaction force (VGRF) within the 0–25% portion of the contact phase after landing. This point reflects the maximum cushioning load, representing the peak of energy absorption immediately following ground contact.
- ② Peak Knee Flexion: The moment at which the knee joint reaches its maximum flexion angle during the contact phase was set as an anchor point, distinguishing the phase transition from eccentric to concentric action.
- ③ Propulsion Inflection: Within the 75–100% section of the contact phase, the Kneedle algorithm was applied to detect the point where the VGRF curve

transitions from a gradual slope to a rapid rise. This represents the shift from accumulated force to propulsive acceleration, corresponding to the phase where concentric force output is intensified.

Normalization (Entire Phase):

The initial contact frame, defined as the first frame where the VGRF continuously exceeds 20 N, was set as 0%, and the take-off frame, defined as the first frame where the VGRF continuously drops below 20 N, was set as 100%. The contact phase was linearly normalized from 0% to 100%. For the main analysis, 51 evenly spaced samples were used, and pchip interpolation was applied.

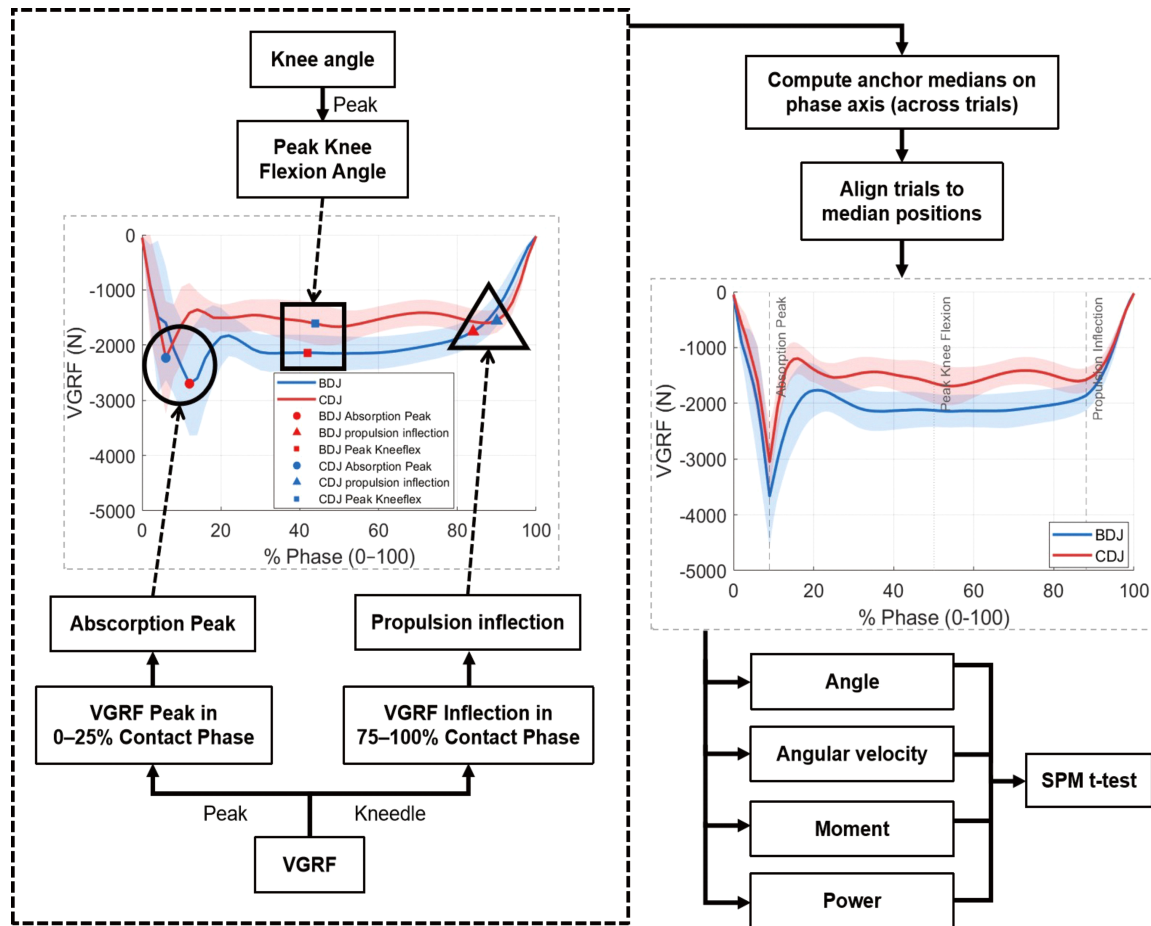


Figure 3. Anchor-Based Temporal Normalization and Phase Alignment Workflow

- Impact Phase: From initial foot contact to the absorption peak
- Cushioning Phase: From the absorption peak to peak knee flexion
- Loading Phase: From peak knee flexion to the propulsion inflection point
- Propulsion Phase: From the propulsion inflection point to take-off

After completing the first phase normalization and identifying the three anchor points (①, ②, ③), the relative duration of the four stages within the overall time axis was first calculated for each trial. Based on the median values obtained from the combined BDJ and CDJ samples, the target proportion of each stage was then determined. To intuitively distinguish between the eccentric and concentric phases, the point of peak knee flexion was fixed at 50% of the timeline.

Subsequently, each trial's time axis was reparameterized linearly within the four segments while maintaining the event timings of the three anchor points, thereby achieving event alignment. As a result, the relative durations of the four segments were 9:41:32:12, and the corresponding anchor point positions were located at 9%, 50%, and 88%, respectively.

Statistical Analysis

All statistical analyses in this study were performed using MATLAB R2024a, and a paired-sample t-test script was executed with the open-source SPM1d toolbox (Pataky, 2021). For all SPM analyses, the statistical significance level was set at $\alpha = 0.05$ across the normalized ground-contact phase. Through this analysis, the joint angular velocity, moment, and power waveforms across the entire contact phase (0–100%) were compared between the BDJ and CDJ conditions, verifying the kinematic and kinetic differences between the two movement strategies.

Results

The aim of this study was to examine the time-varying kinematic and kinetic differences between

bounce drop jumps (BDJ) and countermovement drop jumps (CDJ) across the normalized ground-contact phase (0–100%) for the ankle, knee, and hip joints in the sagittal, frontal, and transverse planes. Statistical Parametric Mapping (SPM_{1d}) was used to identify supra-threshold intervals indicating significant between-condition differences. Results are presented sequentially for joint angle, angular velocity, joint moment, and joint power, followed by an integrated summary of the overall temporal patterns.

SPM-Identified Joint Angle Differences

The SPM analysis revealed that joint-angle differences between BDJ and CDJ were primarily observed at the knee and hip joints, which exhibited broad supra-threshold clusters across the contact phase, extending from early cushioning through the loading phase and into early propulsion (Figure 4). Across these intervals, CDJ demonstrated larger joint-angle excursions in both positive and negative directions. In the frontal plane, BDJ and CDJ exhibited opposing excursion patterns. CDJ showed greater hip abduction and knee valgus during the cushioning phase, whereas BDJ exhibited smaller frontal-plane angular excursions. In contrast, ankle joint-angle differences were limited to short and discrete intervals, occurring at 12–16% of the contact phase ($|CDJ| > |BDJ|$) and 84–94% ($|BDJ| > |CDJ|$) in the sagittal plane, and at 34–66% in the transverse plane, where BDJ exhibited greater external rotation.

SPM-Identified Joint Angular Velocity Differences

The results of the joint angular velocity analysis demonstrated distinct time-dependent differences between BDJ and CDJ across the normalized ground-contact phase (Figure 5). The ankle joint exhibited consistent supra-threshold differences across all three planes, with all significant intervals indicating higher angular velocity in BDJ. In the sagittal plane, significant clusters were observed at 8–38%, 70–82%, and 92–96%, indicating that BDJ exhibited higher

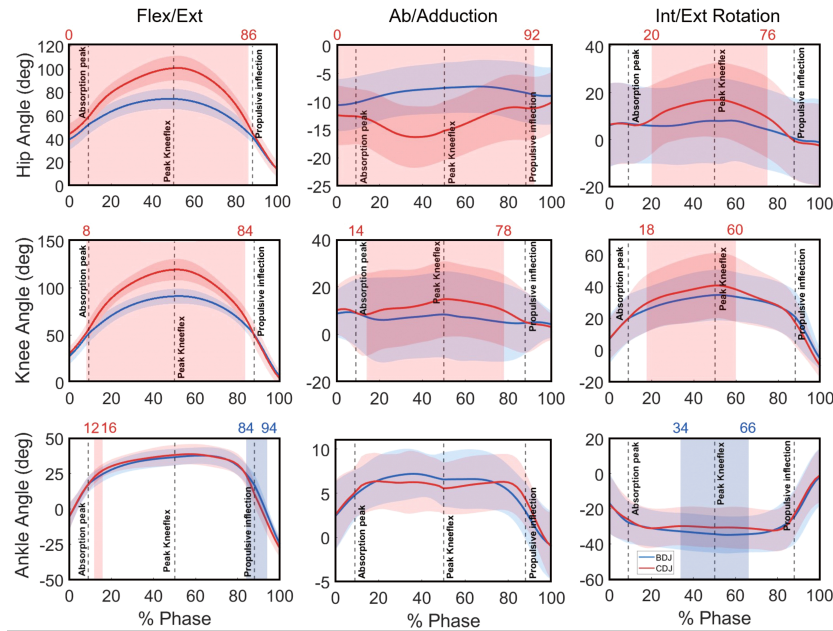


Figure 4. Joint angle time-series and SPM{1d} supra-threshold clusters for the hip, knee, and ankle across three planes during ground contact (0-100%). Red and blue shaded regions indicate phases where $|CDJ| > |BDJ|$ and $|BDJ| > |CDJ|$, respectively. Y-axis scales differ between panels to optimize visualization of joint- and plane-specific kinematic features

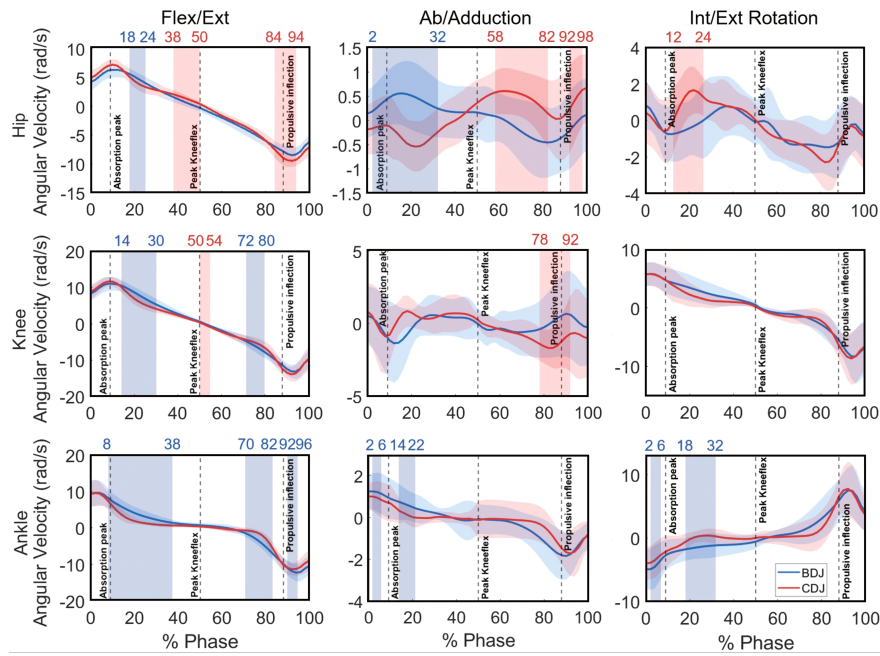


Figure 5. Hip, knee, and ankle angular velocities across three planes during BDJ and CDJ, time-normalized to ground contact (0-100%). Shaded regions indicate SPM{1d} supra-threshold clusters (red: $|CDJ| > |BDJ|$; blue: $|BDJ| > |CDJ|$). Y-axis scales differ between panels to optimize visualization of joint-specific kinematic features

angular velocity during early contact, mid-loading, and late propulsion. In the frontal and transverse planes, early supra-threshold clusters (e.g., 2–6%, 14–22%) similarly indicated greater BDJ angular velocity during initial contact and early cushioning.

The knee joint demonstrated fewer multi-planar differences. In the sagittal plane, BDJ exhibited higher angular velocity at 14–30% and 72–80%, whereas CDJ showed a brief supra-threshold interval at 50–54%. In the frontal plane, a late supra-threshold cluster at 78–92% indicated higher angular velocity in CDJ, while no significant differences were detected in the transverse plane.

The hip joint showed the most extensive plane-dependent differences. In the sagittal plane, BDJ exhibited higher angular velocity during 18–24%, whereas CDJ showed higher values at 38–50% and 84–94%. In the frontal plane, BDJ exceeded CDJ from 2–32%, while CDJ exhibited higher angular velocity during 58–82% and 92–98%. In the transverse plane,

a single early supra-threshold interval at 12–24% indicated higher angular velocity in CDJ. Across the three joints, angular-velocity differences followed a clear distal-to-proximal distribution, with earlier and more frequent supra-threshold intervals at the ankle in BDJ, and broader, later intervals concentrated at the hip in CDJ, varying by anatomical plane.

SPM-Identified Joint Moment Differences

The results of the joint moment analysis demonstrated joint- and phase-specific differences between BDJ and CDJ across the normalized ground-contact phase (0–100%) (Figure 6). In the sagittal plane, most supra-threshold intervals were observed during the cushioning and mid-loading phases. CDJ exhibited larger flexion–extension joint moments than BDJ at the hip (22–30% and 76–80%), knee (30–38% and 64–72%), and ankle (22–28%, 44–52%, 66–78%, 86–90%). In contrast, BDJ showed a greater joint

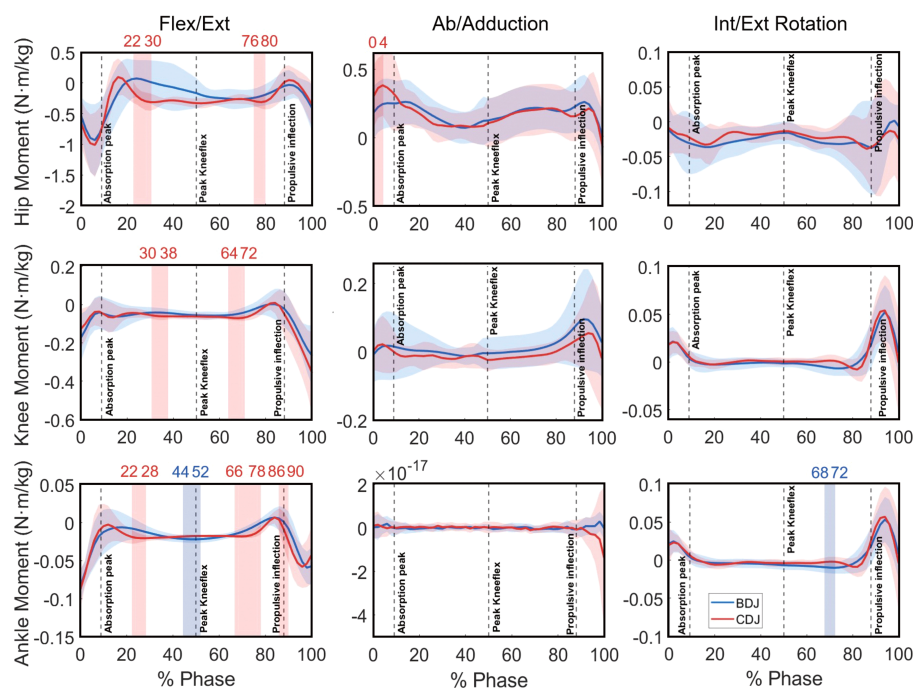


Figure 6. Hip, knee, and ankle joint moments across three planes during BDJ and CDJ, time-normalized to the ground-contact phase (0–100%). Shaded regions represent SPM{1d} supra-threshold clusters (red: |CDJ| > |BDJ|; blue: |BDJ| > |CDJ|). Y-axis scales differ between panels to improve visualization of joint-specific kinetic features

moment only during a brief ankle-specific interval at 44–52%, corresponding to the eccentric–concentric transition period.

In the frontal plane, a single supra-threshold interval was identified at the hip from 0–4%, during which CDJ demonstrated larger abduction–adduction moments. In the transverse plane, only one significant interval was observed at the ankle from 68–72%, where BDJ exhibited a greater internal–external rotational moment. No additional supra-threshold clusters were detected for knee or hip joint moments in the transverse plane.

SPM-Identified Joint Power Differences

The results of the joint power analysis demonstrated limited and joint-specific differences between BDJ and CDJ across the normalized ground-contact phase (0–100%). As shown in Figure 7, significant differences were identified only in several short supra-threshold

intervals across joints and planes.

In the sagittal plane, the ankle exhibited two significant intervals at 34–40% and 86–88%, with BDJ demonstrating greater power during the earlier interval and CDJ during the later interval. The knee and hip each exhibited a single supra-threshold interval, occurring at 62–68% and 36–48%, respectively, during which CDJ demonstrated greater joint power. These sagittal-plane differences were primarily concentrated near the end of the cushioning phase, whereas differences during the propulsion phase were limited to brief, late intervals, and overall power output during propulsion was largely comparable between conditions. In the frontal plane, a single supra-threshold interval was identified at the hip from 6–24%, during which BDJ exhibited greater joint power. No supra-threshold clusters were detected in the transverse plane for joint power at any joint.

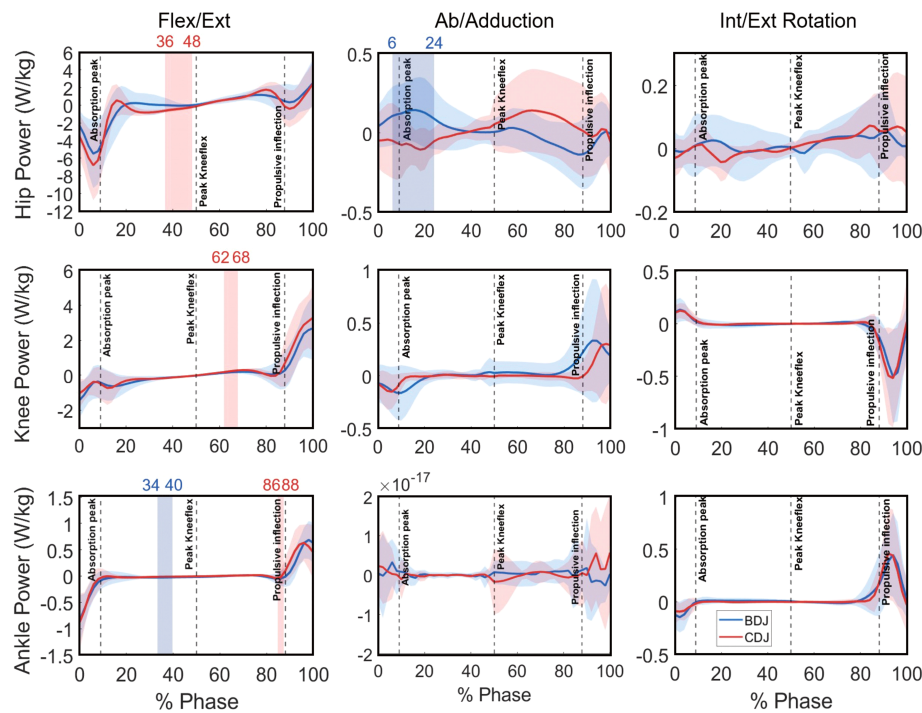


Figure 7. Hip, knee, and ankle joint power across three planes during BDJ and CDJ, time-normalized to the ground-contact phase (0–100%). Shaded regions indicate SPM{1d} supra-threshold clusters (red: |CDJ| > |BDJ|; blue: |BDJ| > |CDJ|). Y-axis scales differ between panels to optimize visualization of joint-specific power patterns

Summary of SPM Results

An integrated examination of the SPM{1d}-identified supra-threshold intervals across joint angles, angular velocities, joint moments, and joint power revealed clear joint- and plane-specific patterns between BDJ and CDJ (Figure 8). Across all three anatomical planes, joint-angle differences were predominantly observed at the hip and knee joints, whereas the ankle exhibited only short and isolated significant intervals. In the frontal plane, the hip demonstrated opposing excursion directions between BDJ and CDJ, which coincided with corresponding supra-threshold intervals in angular velocity.

In the sagittal plane, angular-velocity results exhibited a clear distal-proximal distribution of significant intervals. BDJ showed earlier and more

extensive supra-threshold intervals at the ankle, particularly during impact and early cushioning, whereas CDJ demonstrated broader and more sustained intervals at the hip and knee. Similar joint-dependent tendencies were observed in the frontal and transverse planes, although the extent of significant intervals was reduced.

Regarding joint moments, CDJ exhibited wide and sustained supra-threshold intervals across the hip, knee, and ankle in the sagittal plane, while BDJ showed significant differences only during a brief ankle-dominant interval. In contrast, joint power differences were limited to short and joint-specific supra-threshold intervals, whereas angular velocity and joint moment demonstrated broader and more phase-dependent differences.

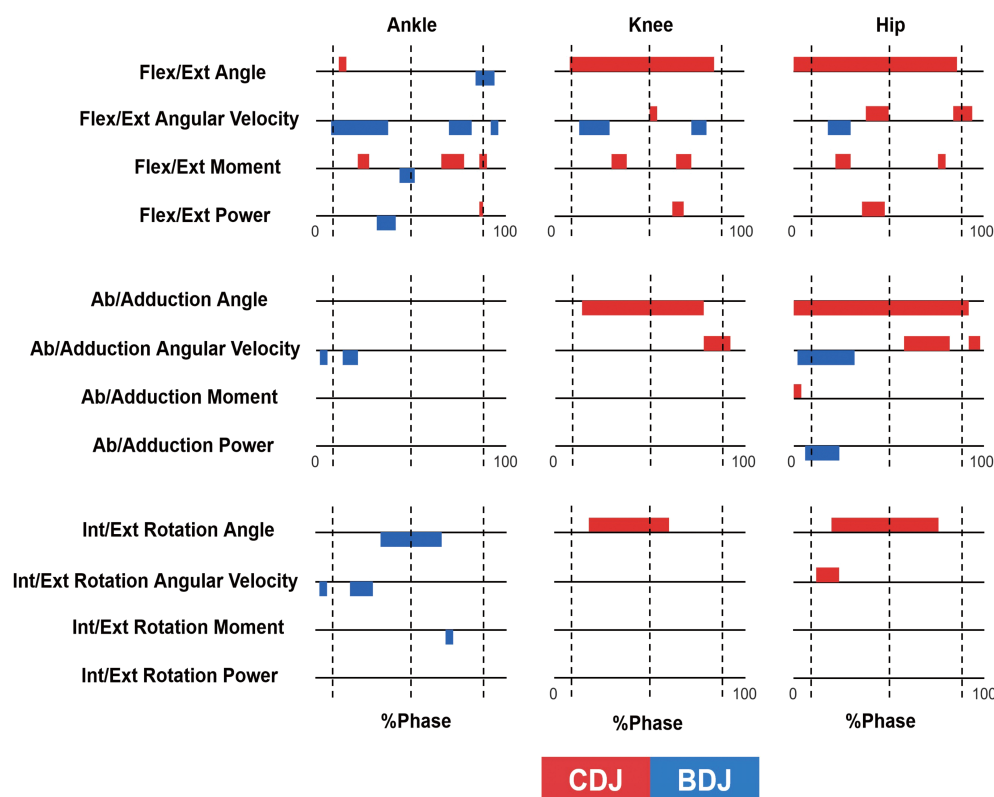


Figure 8. Overview of SPM{1d}-identified significant %Phase intervals for joint angles, angular velocities, moments, and power at the ankle, knee, and hip across three anatomical planes. Bars above and below the baseline indicate phases where $|BDJ| > |CDJ|$ and $|CDJ| > |BDJ|$, respectively; dashed lines denote contact sub-phase landmarks

Discussion

This study aimed to compare the kinematic and kinetic differences between BDJ and CDJ. The joint-angle results indicated that the largest differences between the two techniques occurred at the hip and knee across all three planes, whereas the ankle exhibited only short and relatively small significant intervals. CDJ consistently demonstrated greater proximal joint excursions, reflecting its longer cushioning duration and deeper multiplanar motion. In contrast, the reduced flexion–extension range observed in BDJ originated primarily from restricted hip and knee flexion rather than diminished ankle function.

The frontal-plane analysis further highlighted the distinct strategies of the two techniques. After landing, BDJ shifted from relatively large hip adduction toward progressively reduced adduction, accompanied by a more upright body posture that minimizes lateral displacement and facilitates a rapid, vertically oriented rebound. In contrast, CDJ exhibited greater hip adduction in the early phase to create additional space for deeper cushioning. These findings indicate that frontal-plane hip control is a key determinant of cushioning depth and rebound direction across techniques. Regarding angular velocity, CDJ showed wider significant intervals at the proximal hip and knee joints, whereas BDJ displayed higher angular-velocity characteristics across multiple time periods. The high-speed angular changes observed at the ankle during landing indicate that BDJ relies more on elastic recoil and reflexive activation, rather than large angular displacements (Komi, 2000).

BDJ exhibited two key ankle-level strategies. First, a slightly larger plantarflexion angle appeared during the propulsive phases. Given the limited proximal flexion and extremely short cushioning time, this increased plantarflexion may indicate a greater reliance on ankle contribution during the final push-off (Farris et al., 2016). Second, BDJ showed greater ankle external rotation from late cushioning to early loading. This external rotation may help limit excessive eversion and support immediate mechanical stability when the window for active regulation is extremely limited

(Hertel, 2002). Together, these ankle-level adjustments emphasize a rapid ankle-dominant push-off and rebound strategy under severe temporal constraints.

In jumping movements, energy is usually transmitted sequentially from the proximal to the distal joints (Bobbert & van Ingen Schenau, 1988). However, in BDJ, the extremely short contact time compresses and partly reverses this sequence. The ankle must respond first, producing rapid extension to absorb impact and trigger rebound, while the proximal joints, particularly the hip, have insufficient time to fully develop torque (Bobbert et al., 1986). This pattern supports the interpretation that early stretch of the ankle plantar-flexor system may facilitate rapid force transmission during short-latency SSCs (Kellis & Blazevich, 2022). In addition, elastic energy storage and return around the ankle (e.g., through muscle–tendon and periarticular structures) may enable exchange within a small angular range (Kubo et al., 2000). The ankle also contributes to postural stability by constraining motion to prevent excessive dorsiflexion and maintain coordinated recoil (Komi & Gollhofer, 1997). Therefore, despite limited ankle-angle differences between BDJ and CDJ, the ankle’s rapid and elastically efficient behavior may explain why BDJ shows a more distal-prioritized force-transfer pattern within minimal joint excursion. This strategy may place relatively high demands on ankle joint control and rapid load tolerance; therefore, BDJ may be suitable for athletes requiring short-contact reactive strength, but should be introduced progressively when ankle control or load tolerance is insufficient.

It should be noted that the differences in kinetic variables were predominantly observed in the sagittal plane, whereas frontal- and transverse-plane kinetic differences were limited and more intermittent. In this study, differences in joint power were found primarily during the cushioning and energy storage phases. In the cushioning phase, the negative cluster of the ankle (34–40%) and the positive cluster of the hip (36–48%) were located in close proximity, suggesting a difference in energy distribution between the two movement strategies near the end of cushioning. In contrast, during the energy storage phase, regions where CDJ showed

greater power than BDJ appeared only as short clusters in the later part of the phase.

Most previous studies have relied on discrete indicators, comparing the peak values of joint power. Bobbert et al. reported that the power peaks at the knee and ankle joints were significantly higher in BDJ than in CDJ, interpreting this as evidence that BDJ holds an advantage in terms of mechanical output (Bobbert et al., 1987). In contrast, Walsh et al. reported that as ground contact time decreased, the knee joint power peak actually decreased, and the ankle joint peak did not show any significant increase. They explained that the defining characteristic of BDJ lies not in enhancing the power peak of a specific joint, but in achieving faster energy recycling by shortening contact time and adjusting the distribution of roles among the joints (Walsh et al., 2004). The findings of this study align with the interpretation of Walsh et al. and demonstrate that critical differences emerge within the functional transition between energy storage and propulsion, rather than at discrete power peaks.

CDJ exhibited larger and more sustained joint moments throughout the movement. Except for the late cushioning phase of the ankle (44–52%), all other significant intervals within the cushioning–energy storage phases showed the relationship $|CDJ| > |BDJ|$. CDJ tended to maintain a greater eccentric joint moment from cushioning through energy storage, which can be interpreted as a strategy that extends the cushioning duration and dissipates impact forces through active muscle control responsible for braking and force transmission (Buckthorpe & Della Villa, 2021). Together with the greater proximal joint excursions observed in CDJ, these sustained joint moments indicate that CDJ provides a longer movement window for active force regulation during landing. Therefore, for beginners or athletes with limited landing-control capacity, CDJ may be practiced before progressing to BDJ when the goal is to develop controlled landing mechanics prior to emphasizing rapid rebound performance.

It is noteworthy that during the early and mid-cushioning phases, all three joints showed significant clusters where $|CDJ| > |BDJ|$ for joint

moment, whereas at similar time points, BDJ exhibited significantly greater joint angular velocities. Since joint power is the product of angular velocity and joint moment, opposing tendencies between these variables partially offset differences in joint power. This contrasting relationship between angular velocity and moment was also observed in the ankle joint during the energy storage phase. However, in the late cushioning phase, the ankle joint exhibited high moment and power simultaneously, which was the only interval where both variables were significantly greater in BDJ. This finding suggests that BDJ concentrates energy absorption at the ankle immediately prior to rebound. Therefore, although the total magnitude of energy absorption and output differed little between conditions, the underlying load-distribution strategies were clearly distinct: BDJ appeared to rely more on rapid elastic energy utilization around the distal joints, whereas CDJ emphasized force generation through sustained active joint moments. This phenomenon “similar outcomes but different strategies” has also been reported in basketball players. Rauch et al. classified 178 NBA players into stiff, hyper, and hip-flexor dominant types based on their descent behavior during landing. Although jump height did not differ among groups, distinct temporal and kinetic characteristics were observed, highlighting the relevance of strategy-specific movement solutions (Rauch et al., 2020).

The required physical characteristics vary across sports, and the effectiveness of training depends on the degree of similarity between training exercises and sport-specific movements (Zatsiorsky, 1995). The volleyball block jump analyzed by Zhao et al. demonstrated large hip and knee flexion, increased flexion power, and prolonged energy absorption, features consistent with the CDJ mechanism identified in the present study (Zhao et al., 2024). Similarly, the standing long jump analyzed by Yokozawa et al. exhibited sustained proximal torques and delayed yet forceful hip extension, closely resembling CDJ behavior (Yokozawa et al., 2019). In contrast, maximal-speed sprinting exhibits a distal-dominant, short-contact strategy characterized by high ankle torque, power, and plantarflexion velocity, closely mirroring the BDJ

mechanism (Nagahara & Murata, 2024).

Based on the present findings, BDJ and CDJ should not be regarded as interchangeable drop-jump variations. BDJ may be preferentially used when the training goal is to develop short ground-contact ability, rapid rebound performance, and ankle-dominant reactive output. In contrast, CDJ may be more appropriate when the goal is to develop controlled force absorption, larger hip- and knee-dominant countermovement, and active force production over a longer contact duration. Therefore, CDJ can be used as a preparatory or developmental exercise for athletes who need to improve landing control and force-regulation capacity, whereas BDJ should be applied when athletes are able to maintain posture and joint control under shorter contact-time constraints. Furthermore, combining both techniques may enhance coordination across the kinetic chain by reinforcing proximal-to-distal force transfer, as observed in complex sport movements such as goalkeeper diving (Ibrahim et al., 2020). Importantly, even within the same sport, athletes with comparable performance outcomes may rely on different joint strategies and technical pathways. Therefore, training programs should be individualized based on characteristic movement patterns and force-production rhythms observed in real performance contexts (Kipp et al., 2020).

While these findings provide meaningful implications for sport-specific training, this study focused exclusively on lower-limb joint kinematics and kinetics and did not directly address neuromuscular control mechanisms. Future research integrating electromyography (EMG) would allow deeper insight into the neural activation strategies underlying these mechanical differences.

Conclusions

This study demonstrated that BDJ and CDJ achieve comparable performance outcomes through fundamentally different biomechanical strategies. CDJ is characterized by greater proximal joint excursions and sustained joint moments, reflecting a movement strategy that emphasizes extended cushioning and active force production at the hip and knee. In contrast, BDJ operates

under severe temporal constraints and relies on rapid ankle-driven mechanics, high angular velocities, and efficient elastic energy utilization within a short contact time.

Despite only minor differences in ankle joint angles, BDJ exhibited pronounced ankle angular velocities, joint moments, and power during late cushioning, indicating a redistribution of load toward the distal joint immediately prior to rebound. Conversely, CDJ maintained larger eccentric moments across multiple joints throughout the cushioning and energy storage phases, supporting a strategy of prolonged energy absorption and controlled force transmission. These findings indicate that the key distinction between BDJ and CDJ lies not in peak mechanical output but in how energy is distributed and recycled across the kinetic chain during the transition from landing to take-off. BDJ favors a distal-dominant, elastic-oriented strategy optimized for rapid force transmission, whereas CDJ adopts a proximal-dominant, moment-driven strategy that prioritizes force generation over longer contact durations.

From a practical perspective, CDJ appears more suitable for developing proximal strength and controlled force absorption, while BDJ is better aligned with training goals targeting ankle reactive control, reactive strength, and explosive performance under short ground contact conditions. Importantly, athletes may achieve similar performance outcomes using different joint-level solutions, underscoring the need for individualized training strategies that align exercise selection with sport-specific demands and athlete-specific movement characteristics.

Acknowledgments

This work was supported by the Research Fund of Hanyang University (No. HY- 202500000003787).

Author Contributions

Conceptualization: Pang Haoze, Zhao Rui, Siddhartha Bikram Panday

Data curation: Pang Haoze

Formal analysis: Pang Haoze, Zhao Rui

Investigation: Pang Haoze, Zhao Rui

Project administration: Siddhartha Bikram Panday

Writing-original draft: Pang Haoze,

Writing-review & editing: Siddhartha Bikram Panday,
Lee Seongno, Zhao Rui

Conflict of Interest

The authors declare no conflict of interest.

References

- Bassa, E., Adamopoulos, I., Panoutsakopoulos, V., Xenofondos, A., Yannakos, A., Galazoulas, C., & Patikas, D. A. (2023). Optimal drop height in prepubertal boys is revealed by the performance in squat jump. *Sports*, **11**(1), Article 1.
- Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1986). A model of the human triceps surae muscle-tendon complex applied to jumping. *Journal of Biomechanics*, **19**(11), 887–898.
- Bobbert, M. F., Huijing, P. A., & van Ingen Schenau, G. J. (1987). Drop jumping. I. The influence of jumping technique on the biomechanics of jumping. *Medicine & Science in Sports & Exercise*, **19**(4), 332–338.
- Bobbert, M. F., & van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal of Biomechanics*, **21**(3), 249–262.
- Buckthorpe, M., & Della Villa, F. (2021). Recommendations for plyometric training after ACL reconstruction: A clinical commentary. *International Journal of Sports Physical Therapy*, **16**(3), 879.
- Ciocca, G., Tschan, H., & Tessitore, A. (2021). Effects of post-activation performance enhancement (PAPE) induced by a plyometric protocol on deceleration performance. *Journal of Human Kinetics*, **80**(1), 5–16.
- Dos' Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sports Medicine*, **48**(10), 2235–2253.
- Duan, L., Gao, Y., Gao, F., Sun, Y., & Tian, N. (2025). Analysis of the impact of different landing heights and lateralities on lower limb joint load based on statistical parametric mapping. *PLOS ONE*, **20**(5), e0324656.
- Farris, D. J., Lichtwark, G. A., Brown, N. A., & Cresswell, A. G. (2016). The role of human ankle plantar flexor muscle-tendon interaction and architecture in maximal vertical jumping examined in vivo. *Journal of Experimental Biology*, **219**(4), 528–534.
- Helwig, N. E., Hong, S., Hsiao-Weckslar, E. T., & Polk, J. D. (2011). Methods to temporally align gait cycle data. *Journal of Biomechanics*, **44**(3), 561–566.
- Hertel, J. (2002). Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. *Journal of Athletic Training*, **37**(4), 364–375.
- Ibrahim, R., Kingma, I., de Boode, V., Faber, G. S., & van Dieën, J. H. (2020). Angular Velocity, Moment, and Power Analysis of the Ankle, Knee, and Hip Joints in the Goalkeeper's Diving Save in Football. *Frontiers in Sports and Active Living*, **2**, 13.
- Kellis, E., & Blazeovich, A. J. (2022). Hamstrings force-length relationships and their implications for angle-specific joint torques: a narrative review. *BMC Sports Science, Medicine and Rehabilitation*, **14**(1), 166.
- Kipp, K., Kiely, M., Giordanelli, M., Malloy, P., & Geiser, C. (2020). Joint- and subject-specific

- strategies in male basketball players across a range of countermovement jump heights. *Journal of Sports Sciences*, **38**(6), 652–657.
- Komi, P. V. (2000). Stretch-shortening cycle: a powerful model to study normal and fatigued muscle. *Journal of Biomechanics*, **33**(10), 1197–1206.
- Komi, P. V., & Gollhofer, A. (1997). Stretch reflexes can have an important role in force enhancement during SSC exercise. *Journal of Applied Biomechanics*, **13**(4).
- Kubo, K., Kanehisa, H., Kawakami, Y., & Fukunaga, T. (2000). Elasticity of tendon structures of the lower limbs in sprinters. *Acta Physiologica Scandinavica*, **168**(2), 327–335.
- Lazaridis, S. N., Bassa, E. I., Patikas, D., Hatzikotoulas, K., Lazaridis, F. K., & Kotzamanidis, C. M. (2013). Biomechanical comparison in different jumping tasks between untrained boys and men. *Pediatric Exercise Science*, **25**(1), 101–113.
- Makaruk, H., Porter, J., Czaplicki, A., Sadowski, J., & Sacewicz, T. (2012). The role of attentional focus in plyometric training. *Journal of Sports Medicine and Physical Fitness*, **52**(3), 319–327.
- Marshall, B. M., & Moran, K. A. (2013). Which drop jump technique is most effective at enhancing countermovement jump ability, “countermovement” drop jump or “bounce” drop jump? *Journal of Sports Sciences*, **31**(12), 1368–1374.
- Martinez, D. B. (2016). The use of reactive strength index, reactive strength index modified, and flight time: contraction time as monitoring tools. *Journal of Australian Strength & Conditioning*, **24**(5), 37–41.
- Matic, M. S., Pazin, N. R., Mrdakovic, V. D., Jankovic, N. N., Ilic, D. B., & Stefanovic, D. L. (2015). Optimum drop height for maximizing power output in drop jump: The effect of maximal muscle strength. *The Journal of Strength & Conditioning Research*, **29**(12), 3300–3310.
- Nagahara, R., & Murata, M. (2024). Support leg joint kinetic determinants of maximal speed sprint performance. *Journal of Sports Sciences*, **42**(24), 2506–2516.
- Ortega, D. R., Rodríguez Bies, E. C., & Berral de la Rosa, F. J. (2010). Analysis of the vertical ground reaction forces and temporal factors in the landing phase of a countermovement jump. *Journal of Sports Science and Medicine*, **9**(2), 282–287.
- Pataky, T. (2021). *spm1d 0.4* [Computer software]. Retrieved August 20, 2025, from <https://spm1d.org/>
- Peng, H.-T., Khuat, C. T., Kernozek, T. W., Wallace, B. J., Lo, S.-L., & Song, C.-Y. (2017). Optimum drop jump height in division III athletes: under 75% of vertical jump height. *International Journal of Sports Medicine*, **38**(11), 842–846.
- Rauch, J., Leidersdorf, E., Reeves, T., Borkan, L., Elliott, M., & Ugrinowitsch, C. (2020). Different Movement Strategies in the Countermovement Jump Amongst a Large Cohort of NBA Players. *International Journal of Environmental Research and Public Health*, **17**(17), 6394.
- Ruschel, C., Dell’Antonio, E., Fontana, H. D. B., Haupenthal, A., Hubert, M., Pereira, S. M., & Roesler, H. (2016). Biomechanical analysis of the contact phase in drop jumps performed in water and on dry land. *Revista Brasileira de Cineantropometria & Desempenho Humano*, **18**, 41–49.
- Struzik, A., Juras, G., Pietraszewski, B., & Rokita, A. (2016). Effect of drop jump technique on the reactive strength index. *Journal of Human Kinetics*, **52**, 157–164.
- Walsh, M., Arampatzis, A., Schade, F., & Brüggemann, G.-P. (2004). The effect of drop jump starting

- height and contact time on power, work performed, and moment of force. *The Journal of Strength & Conditioning Research*, **18**(3), 561–566.
- Yokozawa, T., Kumagawa, D., Arakawa, H., Katsumata, Y., & Akagi, R. (2019). A biomechanical analysis of the relationship between the joint powers during the standing long jump and maximum isokinetic strength of the lower limb joints. *International Journal of Sport and Health Science*, **17**, 13–24.
- Young, W. B., Pryor, J. F., & Wilson, G. J. (1995). Effect of instructions on characteristics of countermovement and drop jump performance. *The Journal of Strength & Conditioning Research*, **9**(4), 232–236.
- Zatsiorsky, V. M. (1995). *Science and Practice of Strength Training*. Human kinetics.
- Zhao, H., Liu, X., Dan, L., Xu, D., & Li, J. (2024). Biomechanic differences between anticipated and unanticipated volleyball block jump: Implications for lower limb injury risk. *Life (Basel)*, **14**(11), 1357.