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PHASE-SPECIFIC KINEMATIC AND KINETIC CHARACTERISTICS OF COUNTERMOVEMENT JUMP IN VOLLEYBALL PLAYERS

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ABOUT ARTICLE

Key words: Vertical jump performance; three-dimensional motion capture; squat jump; countermovement jump; joint kinematics; kinetic chain; vertical impulse; elastic energy utilization; postural stability; sports biomechanics.

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Abstract: The purpose of this study was to analyze the biomechanical characteristics of vertical jump performance using three-dimensional motion capture technology. Squat jump and countermovement jump actions were examined in an elite athlete using STT Systems 3DMA (Motive 2023.0) at a sampling frequency of 120 Hz. Kinematic and kinetic parameters were assessed across three key phases: initial position, preparation phase, and lift-off phase. The results reveal phase-dependent joint coordination patterns, effective proximal-to-distal force transfer, and optimized center of gravity (CoG) behavior, which collectively explain the athlete's high jump performance (540 mm). The findings provide objective biomechanical evidence relevant for performance diagnostics and training optimization.

Introduction. Vertical jumping is a key motor action used to evaluate lower-limb explosive power, neuromuscular coordination, and movement efficiency in athletes. It is widely applied in performance diagnostics across many sports, including handball, basketball, volleyball, athletics, and combat sports, where rapid force production and effective vertical displacement are essential. As a result, vertical jump analysis has become an important tool for assessing athletic readiness and training outcomes.

From a biomechanical standpoint, vertical jump performance depends not only on maximal muscle strength but also on the coordination of multi-joint movements and the effective control of the body's center of gravity (CoG). Efficient jumping requires synchronized extension of the ankle, knee, and hip joints, allowing force generated by the lower limbs to be transferred through the kinetic chain with minimal energy loss. The temporal organization of these joint actions plays a decisive role in achieving high take-off velocity and jump height.

A fundamental mechanism underlying vertical jump execution is the stretch–shortening cycle (SSC). During the preparation phase, eccentric muscle action enables elastic energy storage in the muscle–tendon units, particularly in the plantarflexors and knee extensors. The subsequent concentric phase allows this stored energy to be released, enhancing force output and vertical impulse. The effectiveness of the SSC is strongly influenced by joint angles, movement timing, and ground contact duration.

While traditional assessment tools provide global indicators such as jump height or peak force, they do not adequately explain the internal movement structure of the jump. In contrast, three-dimensional motion capture systems allow detailed analysis of joint kinematics, inter-segmental coordination, and CoG dynamics throughout the movement phases.

Therefore, the aim of this study was to perform a phase-specific biomechanical analysis of vertical jump performance using three-dimensional motion capture data, focusing on kinematic and kinetic characteristics that determine effective force production and jump efficiency.

Aim

The aim of this study was to analyze vertical jump performance using three-dimensional motion capture by identifying phase-specific kinematic and kinetic characteristics that determine effective force production, center of gravity control, and take-off efficiency.

Objectives

1. To determine general kinematic and kinetic parameters characterizing overall vertical jump performance using three-dimensional motion capture.
2. To analyze joint kinematics in the initial position to assess postural alignment and movement readiness before jump initiation.
3. To examine eccentric phase joint behavior and ground contact duration to evaluate stretch–shortening cycle efficiency.
4. To identify lift-off phase kinematic and kinetic indicators associated with effective force transmission and take-off velocity.

5. To assess bilateral joint coordination and symmetry during vertical jump execution.

Methodology. The general biomechanical performance profile of the countermovement jump reflects the integrated outcome of neuromuscular coordination, force production capacity, and mechanical efficiency in volleyball players. The combination of kinematic and kinetic indicators characterizes the effectiveness of vertical propulsion and energy utilization during the jump.

The maximum vertical velocity of the center of gravity reaches 2.80 m/s, indicating a high rate of upward acceleration during the concentric phase (Table 1). The associated relative variability (V% = 9.64) demonstrates a moderate level of inter-individual consistency, suggesting that most players achieve comparable velocity profiles at peak propulsion. This level of variability is typical for explosive movements that depend on precise timing of segmental coordination.

Table 1

General biomechanical performance parameters of the countermovement jump in volleyball players

Parameters	Units	Values	σ	V,%
Maximum COG speed:	m/s	2.80	0,27	9,64
Maximum jump height:	mm	540	52	9,63
Maximum jump work:	J	429.79	41,5	9,65
Maximum vertical force:	N	5205	545	10,47
Minimum vertical force:	N	-2375	255	10,74

Maximum jump height attains 540 mm, confirming a well-developed vertical performance capacity in the examined volleyball players. The standard deviation of 52 mm, combined with a V% of 9.63, indicates that jump height is relatively homogeneous across the group. This homogeneity suggests a similar level of lower-limb power and technical efficiency in utilizing the stretch–shortening cycle.

Mechanical work performed during the jump reaches 429.79 J, reflecting the total energy output generated to elevate the body mass against gravity. The relative variability of this parameter (V% = 9.65) closely matches that observed for jump height and center-of-gravity speed, indicating a stable relationship between mechanical work production and achieved vertical displacement. This consistency implies efficient conversion of muscular work into external mechanical output.

Maximum vertical force reaches 5205 N, highlighting the substantial ground reaction forces produced during the propulsion phase. The slightly higher variability (V% = 10.47) suggests greater individual differences in force-generation strategies, likely influenced by differences in body mass, muscle strength, and joint coordination patterns. Nevertheless, the overall magnitude confirms a high force-production capacity typical of trained volleyball players.

Minimum vertical force reaches −2375 N, representing the braking phase during the downward countermovement. The negative value reflects the absorption of mechanical energy prior to push-off, which is a critical component of effective stretch–shortening cycle utilization. The relative variability (V% = 10.74) indicates moderate dispersion, suggesting that while all players employ an eccentric braking strategy, the depth and intensity of force absorption vary between individuals.

Taken together, the biomechanical performance indicators demonstrate a balanced profile of high vertical velocity, substantial force production, and efficient mechanical work output, accompanied by moderate variability across athletes. This combination reflects a technically and physically well-developed countermovement jump pattern, where performance outcomes are achieved through coordinated force absorption and propulsion rather than excessive reliance on any single mechanical parameter.

Results and Discussions. At the initiation of the countermovement jump, volleyball players demonstrate a distinct initial joint configuration that reflects both bilateral coordination and segment-specific asymmetries. Upper-limb joints are characterized by relatively small dispersion values, indicating a stable and reproducible preparatory posture before the downward phase of the jump.

Elbow flexion/extension angles differ between sides, with the left elbow positioned at 28° and the right at 35°, suggesting a more flexed right-side preparatory posture. Despite this angular difference, the relative variability is identical on both sides (V% = 7.14), indicating a comparable level of inter-individual consistency and a well-established motor pattern for elbow positioning at jump initiation. A similar trend is observed at the shoulder joint, where flexion/extension values remain close between sides (18° left vs. 16° right), accompanied by low variability (V% ≈ 8–9), further confirming the stability of upper-limb positioning prior to movement onset (Table 2).

In contrast, lower-limb joints exhibit greater variability, reflecting higher individual differences in preparatory strategies. Hip flexion/extension angles are close to neutral on both sides (−4° left, −2° right), indicating an upright trunk–pelvis alignment at the start position.

However, variability is notably higher on the left side (V% = 20) compared to the right (V% = 15), suggesting less uniform control of hip positioning among players on the left limb.

Knee flexion/extension angles reveal a clear bilateral difference, with greater flexion on the right side (12°) compared to the left (8°). The left knee demonstrates higher relative variability (V% = 12.50) than the right (V% = 9.17), indicating reduced consistency in left-side knee alignment during the preparatory phase. This asymmetry may influence force absorption and redistribution during the subsequent eccentric phase.

Table 2

Initial joint kinematic configuration prior to countermovement jump initiation in volleyball players

LOCAL JOINT ANGLES	eft		,%	ight		,%
Elbow flexion/extension (+/-)	8 º		**,14**	5 º	,5	**,14**
Shoulder flexion/extension (+/-)	8 º	,5	**,33**	6 º	,4	**,75**
Hip flexion/extension (+/-)	4 º	,8	**0**	2 º	,6	**5**
Knee flexion/extension (+/-)	º		**2,5**	2 º	,1	**,17**
Knee internal/external rotation (+/-)	5 º		**0**	2 º	,2	**0**
Knee abduction/adduction (+/-)	4 º	,9	**2,5**	1 º	,1	**0**
Plantar flexion/dorsiflexion (+/-)	0 º	,2	**2**	4 º	,3	**,29**

The most pronounced bilateral discrepancy is observed in knee internal/external rotation. The left knee is positioned in −5°, whereas the right knee reaches 12°, producing a substantial angular difference. Moreover, variability on the left side is twice that of the right (V% = 20 vs. 10), highlighting insufficient stabilization of rotational knee alignment on the left limb at jump initiation. Such dispersion suggests inconsistent transverse-plane control, which may affect mechanical efficiency during force transfer.

A similar pattern is evident in knee abduction/adduction. The left side demonstrates greater deviation (−4°) and markedly higher variability (V% = 22.5) compared to the right side

(−1°, V% = 10). These findings indicate that frontal-plane knee alignment on the left limb is less stable and more individualized, potentially increasing mechanical stress during the countermovement phase.

At the ankle joint, plantar/dorsiflexion angles are higher on the right side (14°) than on the left (10°), suggesting a more pronounced preparatory dorsiflexion on the dominant or more stable limb. Variability follows the same pattern, with lower dispersion on the right side (V% = 9.29) compared to the left (V% = 12), confirming more consistent ankle positioning on the right limb prior to take-off.

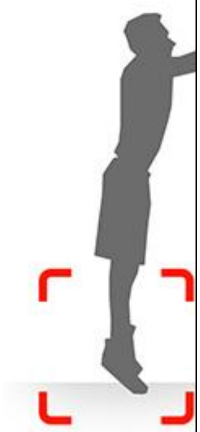
Overall, the initial kinematic configuration is characterized by high bilateral stability in upper-limb joints and greater asymmetry and variability in lower-limb joints, particularly at the knee in rotational and frontal planes. These findings indicate that while arm positioning before the countermovement jump is largely standardized among volleyball players, lower-limb alignment—especially on the left side—shows increased variability, which may influence the efficiency and safety of jump execution.

At the instant of lift-off, volleyball players demonstrate a coordinated extension-dominant movement pattern in which joint kinematics and kinetic outputs collectively determine the effectiveness of vertical propulsion (Table 3). This phase represents the culmination of force transmission through the kinetic chain, where joint alignment, segmental sequencing, and force magnitude converge.

Table 3

Kinematic and kinetic characteristics at lift-off in volleyball players

LOCAL JOINT ANGLES	**eft**	**σ**	**V ,%**	**R ight**		**,%**
Elbow flexion/extension (+/-)	03 º	9 ,8	**,51**	1 01 º	,6	**,50**
Shoulder flexion/extension (+/-)	7 º	8 ,5	**,77**	1 º	,2	**0,11**
Hip flexion/extension (+/-)	7 º	1 ,9	**1,18**	6 º	,5	**,38**
Knee flexion/extension	5 º	4 ,2	**,33**	6 º	,8	**0,43**



(+/-)						
Knee internal/external rotation (+/-)	º	1	**1,11**	3 º	,1	**,13**
Knee abduction/adduction (+/-)	10 º	1 ,1	**1**	5 º	,55	**1**
Plantar flexion/dorsiflexion (+/-)	º	0 ,85	**,44**	4 º	,35	**,64**
EVENT PARAMETERS						
Tibial tilt at lift-off:	- 31 º	,2	0,32	1 º	,9	,35

Parameters	**Units**	**Values**	**σ**	**V, %**
Vertical lift-off speed:	m/s	2.88	0,27	9,38
Vertical lift-off impulse:	Ns	233	24,5	10,52
Vertical lift-off force:	N	1667	158	9,48
Kinetic energy at lift-off:	J	249	26,2	10,52

In the upper limbs, elbow flexion/extension angles reach values above 100° on both sides (103° left, 101° right), indicating near-maximal extension during take-off. The similarity of relative variability between sides (V% ≈ 9.5) reflects a stable and repeatable elbow extension strategy across athletes. Shoulder flexion/extension angles are slightly higher on the right side (91°) than on the left (87°), with comparable variability (V% ≈ 9.8–10.1), suggesting a modest dominant-side contribution of the shoulder segment during the final upward drive.

Hip flexion/extension angles remain relatively small at lift-off (17° left, 16° right), indicating that the hip joint approaches full extension as vertical force peaks. The higher variability observed on the left side (V% = 11.18) compared to the right (V% = 9.38) points to less consistent hip extension control on the left limb, which may influence symmetry of force contribution during propulsion.

Knee flexion/extension angles are nearly symmetrical (45° left, 46° right), confirming synchronized sagittal-plane knee extension at ground separation. Variability remains moderate on both sides, with slightly greater dispersion on the right (V% = 10.43) than on the left (V% = 9.33), reflecting individual differences in the timing and magnitude of terminal knee extension.

More pronounced bilateral differences appear in transverse-plane knee mechanics. Internal/external rotation angles differ substantially between limbs, with the right knee reaching 23° compared to 9° on the left. Despite the higher absolute value on the right, relative variability is greater on the left (V% = 11.11 vs. 9.13), indicating reduced stability of rotational alignment on the left side at take-off. This asymmetry suggests unequal rotational control, which may affect force vector orientation during vertical propulsion.

In the frontal plane, knee abduction/adduction angles differ in magnitude (−10° left, −5° right) while exhibiting identical relative variability (V% = 11). This combination implies consistent inter-individual dispersion but persistent bilateral differences in knee alignment, reflecting athlete-specific frontal-plane strategies at lift-off.

Ankle plantar/dorsiflexion angles increase markedly at take-off, particularly on the right side (14° vs. 9° on the left), indicating a stronger push-off contribution from the right ankle joint. Variability remains low and comparable between sides (V% ≈ 9.4–9.6), confirming controlled and reproducible ankle mechanics during the final propulsion phase.

Event-level parameters further characterize the mechanical effectiveness of lift-off. Tibial tilt angles show opposite directional values between limbs (−31° left, 31° right) with similar variability (V% ≈ 9–10), reflecting symmetrical shank orientation relative to the vertical axis at ground separation. Vertical lift-off speed reaches 2.88 m/s, supported by a vertical impulse of 233 Ns and a peak vertical force of 1667 N, resulting in a kinetic energy output of 249 J at take-off. These values collectively indicate effective conversion of joint-level mechanics into whole-body vertical propulsion.

Overall, the lift-off phase is characterized by high consistency in upper-limb extension, near-symmetrical sagittal-plane lower-limb mechanics, and persistent bilateral asymmetries in transverse and frontal knee alignment, particularly affecting the left limb. This pattern highlights the critical role of lower-limb alignment and rotational control in optimizing vertical jump performance while maintaining mechanical efficiency at take-off.

Conclusion. The present study provides a detailed phase-specific biomechanical characterization of the countermovement jump in volleyball players using three-dimensional motion capture technology. The findings demonstrate that vertical jump performance is determined not by isolated parameters, but by the integrated interaction of kinematic coordination, kinetic output, and center of gravity (CoG) control across movement phases.

Overall performance indicators reveal a high level of explosive capability, as evidenced by a maximum jump height of 540 mm, peak CoG vertical velocity of 2.80 m/s, and substantial mechanical work output. The relatively low coefficients of variation across these parameters indicate a homogeneous performance profile, suggesting consistent technical execution and effective utilization of the stretch–shortening cycle among the athletes.

The analysis of the initial joint configuration highlights pronounced bilateral stability in upper-limb joints, reflecting standardized preparatory arm positioning prior to jump initiation. In contrast, lower-limb joints—particularly the knee—exhibit greater asymmetry and variability, especially in transverse and frontal planes. Elevated variability in knee rotation and abduction/adduction on the left side indicates less stable alignment control at movement onset, which may influence subsequent force transmission efficiency.

During the lift-off phase, the countermovement jump is characterized by near-symmetrical sagittal-plane extension at the hip and knee joints, confirming coordinated proximal-to-distal force transfer. However, persistent bilateral differences in knee rotational mechanics and ankle plantarflexion amplitude remain evident. The right limb demonstrates more pronounced and consistent ankle push-off contribution, suggesting functional dominance in final force production. These asymmetries underline the importance of transverse- and frontal-plane control in optimizing vertical propulsion.

Event-level kinetic parameters further confirm effective mechanical execution, with high vertical lift-off speed, impulse, and kinetic energy values reflecting efficient conversion of stored elastic energy into vertical displacement. The consistency of tibial tilt angles at lift-off supports the presence of controlled shank orientation, contributing to stable take-off mechanics.

In summary, the results indicate that high countermovement jump performance in volleyball players is achieved through a combination of stable upper-limb coordination, effective sagittal-plane force generation, and controlled—but not fully symmetrical—lower-limb alignment. The identified phase-specific asymmetries, particularly at the knee joint, represent important targets for technique refinement and injury-prevention-oriented training interventions. Three-dimensional motion analysis thus proves to be a valuable tool for diagnosing performance structure and guiding evidence-based optimization of vertical jump technique.

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