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KINEMATIC, KINETIC, AND ANTHROPOMETRIC DETERMINANTS OF THE COUNTERMOVEMENT JUMP IN VOLLEYBALL PLAYERS

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ABOUT ARTICLE

Key words: volleyball, countermovement jump, biomechanics, kinematics, kinetics, vertical jump, flight phase, landing phase, center of gravity, ground reaction force, mechanical work, joint angles, knee, ankle, hip, stability, symmetry, asymmetry, movement technique, power, velocity, coordination, stabilization, injury risk, athletes.

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Abstract: This study investigates the biomechanical characteristics of the countermovement jump in volleyball players based on kinematic, kinetic, and anthropometric indicators. Parameters of center of gravity motion, joint angles, vertical ground reaction forces, and mechanical work were analyzed during the preparation, flight, and landing phases. The results demonstrate relatively stable jump height, center of gravity velocity, and mechanical work output, indicating homogeneous explosive performance among athletes. During landing, the knee and ankle joints played a dominant role in impact absorption, while increased variability in frontal and transverse plane motions reflected individual stabilization strategies. These findings provide valuable insights for improving jumping technique and reducing injury risk in volleyball players performing repeated high-intensity vertical actions.

Introduction. Volleyball is a high-intensity team sport characterized by frequent explosive actions, among which vertical jumping plays a decisive role in determining competitive performance. Successful execution of key technical elements such as spiking, blocking, and jump serving largely depends on an athlete's ability to generate and control vertical impulse efficiently. Consequently, the assessment and optimization of jumping mechanics remain a central focus in volleyball-specific sport science research. Among various testing modalities, the countermovement jump (CMJ) is widely used as a standardized and reliable method for evaluating lower-limb explosive power, neuromuscular coordination, and movement efficiency.

From a biomechanical standpoint, CMJ performance emerges from the complex interaction of kinematic and kinetic factors involving multiple body segments and joints. Effective utilization of the stretch–shortening cycle during the preparatory phase allows athletes to store elastic energy in the muscle–tendon units, which is subsequently released during the propulsion phase to enhance vertical displacement. The magnitude and timing of force application, along with coordinated joint motion at the ankle, knee, and hip, are critical determinants of jump height and center of gravity (COG) velocity. Therefore, analyzing these parameters provides insight into the neuromuscular strategies underlying explosive performance in volleyball players.

The CMJ can be divided into distinct phases—preparation, flight, and landing—each associated with specific mechanical demands and movement control requirements. While much attention has traditionally been devoted to the take-off phase, recent studies emphasize the importance of the flight and landing phases in maintaining movement stability and minimizing injury risk. During flight, upper- and lower-limb kinematics contribute to balance control and orientation of the body, whereas during landing, coordinated flexion of the hip, knee, and ankle joints is essential for effective impact absorption. Excessive variability or asymmetry in frontal and transverse plane motions, particularly at the knee joint, has been associated with increased mechanical loading and potential overuse injuries.

Despite the extensive application of CMJ assessments in volleyball, many investigations focus on isolated parameters such as jump height or peak force, without integrating kinematic, kinetic, and anthropometric characteristics across multiple phases of movement. This limitation restricts the understanding of how structural features and joint coordination patterns influence overall jumping performance and stability. A comprehensive phase-based biomechanical analysis can therefore provide a more complete representation of CMJ execution, highlighting both performance-related and injury-related factors.

In this context, the present study aims to examine the kinematic, kinetic, and anthropometric characteristics of the countermovement jump in volleyball players, with particular attention to flight and landing phase mechanics. By identifying patterns of movement consistency, variability, and bilateral symmetry, the study seeks to contribute to the scientific basis for optimizing training interventions and improving the safety and effectiveness of repetitive jumping actions in volleyball.

Aim

The aim of this study is to conduct a comprehensive biomechanical evaluation of the countermovement jump in volleyball players by integrating kinematic, kinetic, and anthropometric parameters across preparation, flight, and landing phases in order to identify movement consistency, joint coordination patterns, bilateral symmetry, and stabilization strategies associated with explosive vertical performance and injury risk reduction.

Objectives

To analyze kinematic characteristics of the countermovement jump across preparation, flight, and landing phases in competitive volleyball players elite athletes.

To evaluate kinetic parameters including vertical ground reaction forces, mechanical work, and force variability during explosive jumping actions in volleyball.

To determine center of gravity displacement patterns and velocity characteristics associated with effective vertical jump performance in volleyball players populations.

To examine joint kinematics and bilateral symmetry of ankle, knee, and hip joints during flight and landing phases in jumping.

To identify variability and stabilization strategies related to injury risk and movement efficiency during repeated volleyball jumping tasks among athletes.

Methodology. The biomechanical analysis of the countermovement jump in volleyball players reveals a relatively homogeneous structure of kinematic and kinetic performance indicators, reflecting stable execution of explosive vertical movements. The mean maximum center of gravity (COG) speed reached 2.80 m/s, with a standard deviation of 0.27 and a coefficient of variation of 9.64%. Such a low dispersion indicates a consistent acceleration pattern during the propulsion phase, suggesting that the majority of athletes apply force to the ground in a coordinated and temporally optimized manner. This level of COG speed is indicative of effective neuromuscular synchronization between the ankle, knee, and hip joints during the concentric phase of the jump.

The maximum jump height averaged 540 mm, demonstrating a well-developed ability to convert vertical impulse into displacement. Although the absolute standard deviation reached 52 mm, the variability coefficient remained below the critical threshold of 10% (9.63%), confirming that jump performance is relatively uniform across the sample. From a biomechanical perspective, this indicates that athletes employ similar movement strategies in terms of countermovement depth and take-off mechanics, allowing for comparable vertical outcomes (Table 1).

Table 1

General biomechanical performance parameters of the countermovement jump in volleyball players

Parameters	Units	Values $\bar{X}$	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

Anthropometrics

Segment	Units	Left			Difference	Right		
		Values $\bar{X}$	σ	V,%		Values $\bar{X}$	σ	V,%
Shoulder height:	mm	1535	148	9,64	**14**	1521	146	9,6
Trochanter height:	mm	966	101	10,46	**6**	973	100	10,28
Femoral length:	mm	51249896	4870000	9,5	**8875132**	42374764	4020000	9,49
Fibular length:	mm	15191572	1610000	10,6	**68793680**	83985248	8720000	10,38
Foot length:	mm	28363924	2720000	9,59	**89728000**	118091928	11050000	9,36

Results and Discussions. Mechanical work performed during the jump amounted to 429.79 J, with a standard deviation of 41.5 J and a variability coefficient of 9.65%. These values reflect a stable mechanical output during the propulsion phase, indicating efficient transformation of muscular force into external work. The consistency of this parameter suggests that the athletes maintain comparable force–displacement relationships, which is essential for repeatable jumping performance in volleyball-specific actions such as blocking and attacking.

The kinetic analysis shows that the maximum vertical force reached 5205 N, while the minimum vertical force during the countermovement phase was −2375 N. The variability coefficients for these parameters were 10.47% and 10.74%, respectively, indicating moderate dispersion. The negative minimum force value characterizes the braking phase, during which elastic energy is stored in the muscle–tendon units. The subsequent high positive force output reflects an effective utilization of this stored energy during the concentric phase, which is a key biomechanical mechanism underlying explosive jumping ability.

Anthropometric analysis demonstrates relatively balanced structural development between the left and right sides. Shoulder height differed by 14 mm, while trochanter height showed a difference of 6 mm, indicating minimal asymmetry in upper-body and pelvic alignment. In contrast, larger absolute bilateral differences were observed in lower-limb segments. Femoral length, fibular length, and foot length exhibited notable side-to-side discrepancies; however, their coefficients of variation ranged between 9.36% and 10.60%, remaining within acceptable biomechanical limits. These findings suggest that, although anatomical asymmetry exists, it does not exceed thresholds that would significantly disrupt movement symmetry or force transmission during vertical jumping tasks.

Taken together, the observed kinematic, kinetic, and anthropometric indicators form a coherent biomechanical profile characterized by stable COG velocity, sufficient jump height, consistent mechanical work production, and controlled force application. The moderate variability coefficients across all parameters indicate a relatively homogeneous group in terms of explosive strength and movement strategy, supporting the athletes' readiness for repeated high-intensity vertical actions that are fundamental to volleyball performance.

The kinematic analysis of the flight phase reveals detailed characteristics of joint behavior and whole-body displacement during the airborne portion of the countermovement jump. Upper-limb kinematics show that elbow flexion/extension angles demonstrate high consistency between sides, with mean values of 111° for both the left and right arms. The coefficients of variation remained below 10%, indicating stable arm positioning during flight, which is essential for maintaining balance and contributing to vertical momentum control

Shoulder flexion/extension exhibited moderate asymmetry between sides, with mean values of 48° on the left and 42° on the right. Despite this difference, variability coefficients remained close to the 10% threshold, suggesting that individual movement strategies differ slightly, but overall shoulder motion remains functionally stable. Such shoulder positioning plays an important role in controlling angular momentum and stabilizing the trunk during airborne phases.

Lower-limb joint kinematics demonstrate more pronounced variability, particularly in knee and hip motions. Hip flexion/extension angles showed small mean values (3° on the left and 2° on the right), accompanied by relatively high variability coefficients exceeding 10%. This indicates that athletes adopt individualized hip control strategies during flight, likely influenced by differences in take-off mechanics and trunk positioning. (Table 2).

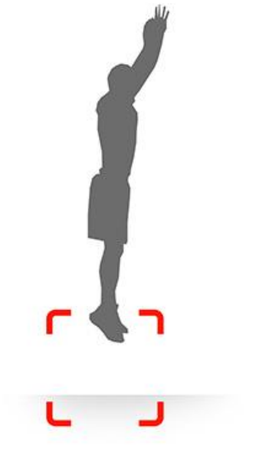
Table 2

Flight phase kinematic parameters of the countermovement jump in volleyball players

LOCAL JOINT ANGLES	Left					Right				
	Min	Max	Values $\bar{X}$	σ	V,%	Min	Max	Values $\bar{X}$	σ	V,%
Elbow flexion/ extension (+/-)	103 º	115 º	111 º	10,6	9,55	101 º	116 º	111 º	10,2	9,19
Shoulder flexion/ extension (+/-)	32 º	88 º	48 º	4,7	9,79	22 º	94 º	42 º	4,4	10,48
Hip flexion/ extension (+/-)	-1 º	17 º	3 º	0,32	10,67	-4 º	16 º	2 º	0,22	11
Knee flexion/ extension (+/-)	-4 º	45 º	3 º	0,28	9,33	-1 º	46 º	5 º	0,48	9,6
Knee internal/ external rotation (+/-)	-12 º	9 º	-9 º	0,95	10,56	1 º	23 º	5 º	0,55	11
Knee abduction/ adduction (+/-)	-10 º	-1 º	-3 º	0,34	11,33	-5 º	0 º	-1 º	0,11	11
Plantar flexion/ dorsiflexion (+/-)	-39 º	9 º	-32 º	3,1	9,69	-37 º	14 º	-29 º	2,7	9,31

PHASE PARAMETERS

Parameters	Units	Values $\bar{X}$	σ	V,%
Flight duration:	s	0.62	0,067	10,81
Flight height:	mm	540	51	9,44
COG horizontal displacement:	mm	78	7,6	9,74

Parameters	Units	$\overline{X}$	σ	V,%	$\overline{X}$	σ	V,%	
Feet horizontal displacement:	mm	120	11,2	9,33	146	15,1	10,34	

Knee flexion/extension angles displayed greater amplitude, with mean values of 3° on the left and 5° on the right. The variability coefficients remained below or close to 10%, reflecting a relatively controlled knee position during flight, which is critical for preparing the lower limbs for landing. Knee internal/external rotation and abduction/adduction angles exhibited higher variability, with coefficients exceeding 10%, indicating less uniform rotational control in the frontal and transverse planes. Such variability may increase mechanical loading during landing and suggests the need for targeted neuromuscular stabilization training.

Ankle kinematics showed substantial plantar flexion during flight, with mean values of −32° on the left and −29° on the right. The relatively low variability coefficients indicate consistent ankle positioning, reflecting effective utilization of the ankle joint in generating and maintaining vertical displacement.

Phase parameters further characterize the flight phase mechanics. The average flight duration reached 0.62 s, with a variability coefficient of 10.81%, reflecting moderate inter-individual differences in airborne time. The achieved flight height averaged 540 mm, confirming a high vertical displacement capacity. Horizontal displacement of the center of gravity averaged 78 mm, indicating limited forward motion and a predominantly vertical jump strategy. In contrast, feet horizontal displacement showed side-specific differences, with greater displacement observed on the right side, suggesting asymmetrical lower-limb contribution to forward motion during take-off and flight.

Collectively, the joint kinematics and phase parameters indicate that while sagittal-plane movements of major joints remain relatively stable, frontal and transverse plane motions exhibit greater variability. This combination reflects both effective vertical propulsion and individualized control strategies during flight, which are characteristic of volleyball players performing repeated explosive jumps under dynamic conditions.

The kinematic analysis of the landing phase highlights the mechanisms by which volleyball players absorb impact forces and stabilize body posture following the flight phase of the countermovement jump. Upper-limb joint behavior during landing demonstrates controlled positioning, with elbow flexion/extension mean values of 100° on the left and 104° on the right. The variability coefficients remained below 10%, indicating a stable arm configuration that contributes to balance control and shock attenuation upon ground contact

Shoulder flexion/extension angles averaged 27° on the left and 26° on the right, with variability values close to the 10% threshold. This moderate dispersion suggests slight inter-individual differences in upper-body posture during landing, which may reflect variations in trunk inclination and arm swing deceleration strategies. Nevertheless, the relatively symmetrical shoulder positioning indicates coordinated upper-body involvement in landing stabilization.

Lower-limb joint kinematics reveal a pronounced role of the hip and knee joints in impact absorption. Hip flexion/extension angles showed identical mean values of 13° for both sides, accompanied by variability coefficients below 10%. This symmetry indicates a balanced contribution of the hip joint to energy dissipation and trunk stabilization during landing. In contrast, knee flexion/extension angles exhibited higher amplitudes, reaching mean values of 50° on the left and 52° on the right. The variability coefficients slightly exceeded 10%, reflecting individual differences in knee flexion depth, which is a key determinant of landing stiffness and vertical load attenuation.

Rotational knee kinematics demonstrated increased variability. Knee internal/external rotation angles showed mean values of 13° on the left and 24° on the right, with variability coefficients approaching or exceeding 10%. This asymmetry suggests unequal transverse-plane control between limbs, which may influence joint loading patterns during landing. Similarly, knee abduction/adduction angles revealed noticeable side-to-side differences, with a greater variability on the right side, indicating less uniform frontal-plane stabilization. Such variability may increase mechanical stress on passive knee structures if not adequately controlled. (Table 3).

Table 3

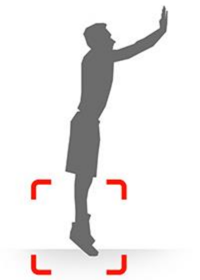
Landing phase kinematic parameters of the countermovement jump in volleyball players

LOCAL JOINT ANGLES	Left					Right				
	Min	**Max**	**Value s $\bar{X}$**	**σ**	**V,%**	**Min**	**Max**	**Value s $\bar{X}$**	**σ**	**V,%**

Elbow flexion/ extension (+/-)	93 º	115 º	100 º	9,4	9,4	99 º	116 º	104 º	9,9	9,52
Shoulder flexion/ extension (+/-)	23 º	32 º	27 º	2,8	10,37	23 º	30 º	26 º	2,6	10
Hip flexion/ extension (+/-)	3 º	21 º	13 º	1,2	9,23	3 º	22 º	13 º	1,25	9,62
Knee flexion/ extension (+/-)	17 º	72 º	50 º	5,3	10,6	19 º	78 º	52 º	5,5	10,58
Knee internal/ external rotation (+/-)	1 º	21 º	13 º	1,4	10,77	13 º	31 º	24 º	2,2	9,17
Knee abduction/ adduction (+/-)	-15 º	-7 º	-11 º	1	9,09	-6 º	3 º	-2 º	0,23	11,5
Plantar flexion/ dorsiflexion (+/-)	-19 º	39 º	18 º	1,7	9,44	-16 º	43 º	22 º	2	9,09

PHASE PARAMETERS

Parameters	Units	Values $\overline{X}$	σ	V,%
Landing duration:	s	0.46	0.050	10.87
Preparation to landing height difference:	mm	230	22.1	9.61



Ankle joint behavior during landing was characterized by plantar flexion angles averaging 18° on the left and 22° on the right. The relatively low variability coefficients indicate consistent ankle positioning, highlighting the ankle's critical role in the initial phase of ground contact and impact absorption. Controlled plantar flexion allows gradual force transfer from the foot to proximal joints, reducing peak loading rates.

Phase parameters further describe the temporal and spatial characteristics of landing. The mean landing duration reached 0.46 s, with a variability coefficient of 10.87%, reflecting moderate differences in impact absorption timing among athletes. The preparation-to-landing height difference averaged 230 mm, indicating the vertical distance over which athletes decelerate the body before full ground contact. This parameter reflects the effectiveness of pre-activation and eccentric muscle control during landing preparation.

Overall, the landing phase kinematics demonstrate that volleyball players employ a coordinated multi-joint strategy characterized by substantial knee flexion, symmetrical hip involvement, and controlled ankle plantar flexion to dissipate impact forces. However, increased variability in frontal and transverse plane knee motions suggests the presence of individual stabilization strategies that may influence joint loading and injury risk, particularly under repeated jumping conditions.

Conclusion. The present study provides a comprehensive biomechanical characterization of the countermovement jump in volleyball players by integrating kinematic, kinetic, and anthropometric parameters across preparation, flight, and landing phases. The findings demonstrate that volleyball players exhibit relatively homogeneous explosive performance, as reflected by stable values of jump height, center of gravity velocity, and mechanical work output. Low to moderate coefficients of variation across these indicators suggest consistent neuromuscular coordination and effective utilization of the stretch–shortening cycle during vertical jumping actions.

The kinematic analysis revealed that sagittal-plane movements of major joints, particularly at the ankle, knee, and hip, remain relatively stable during both flight and landing phases. This stability supports efficient vertical propulsion and controlled body positioning in airborne conditions. In contrast, increased variability was observed in frontal and transverse plane joint motions, especially at the knee joint. Such variability reflects individual stabilization strategies and may represent adaptive mechanisms to maintain balance; however, it may also contribute to elevated mechanical loading and potential injury risk during repeated jumping tasks.

Kinetic findings highlighted the importance of force modulation during the countermovement and landing phases. High peak vertical forces combined with controlled negative forces during braking indicate effective storage and release of elastic energy. During landing, coordinated flexion of the hip, knee, and ankle joints played a key role in impact absorption, reducing excessive loading rates. The observed bilateral symmetry in most anthropometric and kinematic parameters suggests balanced structural development, although minor asymmetries in lower-limb segments underline the need for individualized movement assessment.

Overall, the integration of kinematic, kinetic, and anthropometric data allowed the identification of a coherent biomechanical profile characteristic of volleyball-specific jumping performance. These results emphasize that optimal CMJ execution is not solely determined by jump height or force magnitude, but by the quality of inter-joint coordination and movement control across all phases of the jump. From a practical perspective, the findings support the inclusion of phase-specific biomechanical monitoring in training programs aimed at enhancing explosive performance and reducing injury risk. Future research should focus on longitudinal analyses and intervention-based studies to further clarify how targeted neuromuscular training influences joint stabilization strategies and jumping efficiency in volleyball players.

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