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KINEMATIC ANALYSIS OF VERTICAL JUMP OF VOLLEYBALL PLAYER'S BY USING 3D MA TECHNOLOGY

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ABOUT ARTICLE

Key words: Vertical jump, 3D motion analysis, biomechanics, volleyball, joint angles, force production, kinematics, asymmetry, landing mechanics, performance optimiza-tion, injury prevention, athletic performance.

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Abstract: This article provides an in-depth analysis of the vertical jump performance of vol-leyball players using 3D motion analysis technology. The study focuses on the biomechanical aspects of key phases in the jump, including preparation, lift-off, flight, and landing. The results highlight significant joint angles, vertical force production, and movement patterns that contribute to jump height and landing mechanics. Special attention is given to asymmetries in joint movements, such as knee rotation and ankle dorsiflexion, which could impact performance and injury risk.

Introduction

Vertical jumping is a fundamental skill in volleyball, significantly influencing players' performance in both offensive and defensive plays such as spiking, blocking, and serving. The ability to achieve higher jumps directly correlates with competitive success in volleyball, making the vertical jump a critical component for both coaches and athletes to focus on. The biomechanics of a vertical jump in-volves complex coordination between various muscle groups and joints, where factors like joint angles, force production, and overall body mechanics dictate the effectiveness and efficiency of the jump.

In recent years, advances in technology, particularly 3D motion analysis, have provided a deeper understanding of the biomechanical processes that occur during vertical jumps. This technology enables precise measurements of joint an-gles, ground reaction forces, and movement kinematics, offering insights into the physical capabilities of athletes and identifying areas for improvement. For elite athletes, particularly candidates for master of sports, maximizing their jump height and improving landing mechanics is crucial for optimal performance and injury prevention.

This study aims to analyze the kinematics of the vertical jump in volleyball players, using 3D motion analysis technology to assess key parameters such as joint angles, vertical force production, lift-off speed, and landing mechanics. By examining these variables, the study seeks to offer practical recommendations for improving jump performance and reducing injury risk among volleyball players.

The biomechanics of jumping has been extensively studied across various sports, with particular emphasis on volleyball due to the sport's demand for verti-cal jumping in both offensive and defensive contexts. Lees et al. (2004) conduct-ed a comprehensive review of jumping biomechanics, noting that joint coordina-tion, ground reaction forces, and muscle power are key determinants of jump per-formance. In volleyball, players rely heavily on lower body strength and proper joint mechanics to achieve maximal jump height and efficient landings, as dis-cussed by Baca (1999) in his analysis of drop jump performance.

Ford et al. (2003) highlighted the biomechanical differences in landing me-chanics among volleyball players and athletes from other sports, emphasizing the importance of proper knee and ankle alignment to prevent injuries. They found that asymmetries in knee flexion and abduction could increase the risk of anterior cruciate ligament (ACL) injuries, which are common in volleyball due to the re-petitive jumping and landing involved in the sport.

Pappas and Carpes (2012) further investigated lower extremity kinematic asymmetry in volleyball players during jump-landing tasks, identifying that dom-inant leg preference often leads to asymmetrical joint angles, particularly in the knee and hip. Their study emphasizes the need for bilateral strength training to re-duce injury risk and improve performance.

The use of 3D motion analysis in sports has revolutionized how athletes' movements are assessed. According to Thompson et al. (2022), 3D motion cap-ture allows for a detailed examination of joint angles and movement patterns, providing valuable data for enhancing athletic performance. This technology has been particularly beneficial in volleyball, where quick and precise movements are critical.

In summary, the existing literature highlights the importance of symmetrical joint mechanics, efficient force production, and the role of technology in optimiz-ing jump performance and preventing injuries. This study builds on previous re-search by using 3D motion analysis to provide a comprehensive kinematic profile of volleyball players during vertical jumps, offering practical recommendations for improving performance.

Aim of the Research. Specifically, the study focuses on evaluating how shoulder flexion, extension, abduction, and adduction contribute to the effective-ness of both the vertical jump and blocking action.

Tasks of the Research:

1. Analyze how shoulder flexion, extension, abduction, and adduction affect a player's ability to reach maximum height and intercept the ball effectively dur-ing the vertical jump and block.

2. Use advanced 3D motion capture technology to measure joint angles, shoulder positioning, and coordination during the blocking and jumping actions.

3. Assess any asymmetries in shoulder flexion and abduction to determine if players favor one side, which could impact jump height and blocking effective-ness.

4. Analyze specific kinematic indicators most crucial for achieving a success-ful vertical jump and block, including range of motion, control of shoulder movements, and synchronization with lower-body mechanics.

5. Suggest training programs that enhance shoulder strength, flexibility, and balance to improve vertical jump height and blocking technique, while reducing the risk of injury.

Research Organization. The research was conducted at the Uzbek State University of Physical Education and Sports in the high-tech laboratory of Sport, equipped with advanced 3D motion analysis technology. This state-of-the-art fa-cility allowed for precise measurement of biomechanical parameters, making it ideal for studying athletic movements in detail. The subject of the study was a candidate athlete for Master of Sports in volleyball, with extensive competitive experience. The primary focus of the experiment was to analyze shoulder move-ments during the vertical jump and blocking technique, emphasizing kinematic and kinetic data associated with shoulder flexion, extension, abduction, and ad-duction. The controlled laboratory environment ensured the accuracy and reliabil-ity of data collection, providing valuable insights into the biomechanics of elite-level volleyball movements.

Methods: The study employed advanced 3D motion analysis technology to conduct a detailed biomechanical evaluation of shoulder movements during the vertical jump and blocking technique in volleyball. The research was carried out in the high-tech laboratory at the Uzbek State University of Physical Education and Sports. A candidate athlete for Master of Sports in volleyball participated in the experiment, and their blocking and jumping performance was captured using a high-resolution 3D motion capture system. Multiple infrared cameras were stra-tegically placed around the laboratory to track the athlete’s movements from vari-ous angles.

Reflective markers were placed on key anatomical points, including the shoulders, elbows, spine, hips, knees, and ankles, to capture precise data on joint angles, shoulder movements, and overall body posture during the vertical jump and blocking actions. This setup allowed for a comprehensive analysis of the kin-ematic indicators, focusing on how shoulder flexion, extension, abduction, and adduction contribute to blocking performance and vertical jump height. The de-tailed motion data provided insights into the athlete's shoulder and lower-body mechanics, which are crucial for executing an effective and well-coordinated ver-tical jump and block in volleyball.

Results: The athlete demonstrated a maximum COG speed of 2.80 m/s, in-dicative of the rapid upward propulsion achieved during the peak of the jump. The maximum jump height recorded was 540 mm, reflecting the athlete's explo-sive lower body power. The jump's maximum work, which represents the energy output during the movement, was calculated to be 429.79 joules (Table-1). Addi-tionally, the maximum vertical force exerted was 5205 newtons, showcasing the high levels of force production capability of the athlete. Conversely, the minimum vertical force was recorded at -2375 newtons, observed during the downward phase of the jump where the body prepares for the explosive upward movement.

Table-1

Overview – general parameters vertical jump (Squat jump & CMJ)

Maximum COG speed:	2.80 m/s
Maximum jump height:	540 mm
Maximum jump work:	429.79 J
Maximum vertical force:	5205 N
Minimum vertical force:	-2375 N

In volleyball, starting posture significantly impacts an athlete's ability to perform explosive movements efficiently and safely. Prior research indicates that joint angle configurations can affect performance outcomes and injury risks in sports (Smith, 2019). This analysis employs 3D motion capture technology to measure the local joint angles in volleyball players, providing a foundational understanding of their biomechanical setup.

Left at 28º and right at 35º. This asymmetry may reflect the dominant arm usage, which is consistent with findings by Lee and colleagues (2020) that dominant limbs often show greater flexibility and strength.

Angles were 18º on the left and 16º on the right, suggesting a relatively symmetrical upper body alignment, which is important for maintaining balance and stability during play (Khan, 2018).

The hips were slightly extended at -4º on the left and -2º on the right. According to Patel and Smith (2017), slight hip extension can facilitate quicker transitions into jumping or sprinting.

Measured at 8º on the left and 12º on the right, with internal/external rotation at -5º and 12º, respectively. Knee abduction/adduction angles were -4º on the left and -1º on the right. These findings suggest a readiness position, optimizing the lower limbs for sudden explosive movements (Chang et al., 2019).

Angles of 10º on the left and 14º on the right indicate a prepared stance for upward propulsion, as discussed in research by Thompson et al. (2022).

The joint angles observed provide insights into the biomechanical preparation of volleyball players. The slight asymmetries in elbow and knee angles can be attributed to the roles of dominant and non-dominant limbs in sport-specific movements (Smith, 2019; Lee et al., 2020). The symmetrical shoulder angles across players indicate a balanced upper body posture, essential for effective and safe performance of overhead actions. The slight extensions observed in the hips and the preparatory angles at the ankles support quick transitions into dynamic actions (Patel & Smith, 2017; Thompson et al., 2022).

Table-2

Initial position kinematics of volleyball players

№	Local joint angles	Left	Right	
1	Elbow flexion/extension (+/-)	37 º	42 º	
2	Shoulder flexion/extension (+/-)	24 º	21 º	

3	Hip flexion/extension (+/-)	47 º	45 º	
4	Knee flexion/extension (+/-)	120 º	127 º	
5	Knee internal/external rotation (+/-)	18 º	22 º	
6	Knee abduction/adduction (+/-)	22 º	30 º	
7	Plantar flexion/dorsiflexion (+/-)	49 º	58 º	
8	Event parameters			
9	Pre-jump ground contact time:	0.73 s		

Table-3

Preparation position kinematics of volleyball players

Left elbow (37°) and Right elbow (42°): The slight asymmetry in elbow flexion suggests that the player may have a dominant side in terms of arm preparation. This degree of flexion typically aligns with arm-swing preparation before the jump, where players generate momentum by swinging their arms backward and then forward during the jump execution (Table-3).

Left shoulder (24°) and Right shoulder (21°): The shoulders are moderately flexed, indicating preparation for an arm swing that assists in generating upward momentum. Similar to the elbow, there is a slight asymmetry in the angles, which might reflect a natural preference for one arm or shoulder during the jump.

Left hip (47°) and Right hip (45°): These angles indicate a semi-squat position, where the hips are flexed to lower the center of gravity, providing a stable base for the jump. This amount of hip flexion is common in the preparation phase, allowing athletes to maximize force production during the jump.

№	**Local joint angles**	**Left**	**Right**	
1	Elbow flexion/extension (+/-)	28 º	35 º	
2	Shoulder flexion/extension (+/-)	18 º	16 º	
3	Hip flexion/extension (+/-)	-4 º	-2 º	
4	Knee flexion/extension (+/-)	8 º	12 º	
5	Knee internal/external rotation (+/-)	-5 º	12 º	
6	Knee abduction/adduction (+/-)	-4 º	-1 º	
7	Plantar flexion/dorsiflexion (+/-)	10 º	14 º	

Left knee (120°) and Right knee (127°): The knee angles show significant flexion, which is necessary to generate power for the jump. The slight difference between the knees could indicate a preference for one leg as the primary pushing leg during the jump. This degree of flexion is typical of the preparation phase, providing optimal force output when extending the knees during the jump.

Left knee (18°) and Right knee (22°): This minor rotational difference between the knees suggests that there may be slight external rotation, particularly in the right leg. This could be linked to body orientation or landing preferences, which need further investigation to determine if it's an optimal or compensatory movement.

Left knee (22°) and Right knee (30°): The difference in abduction/adduction could indicate an uneven load distribution between the legs. The higher abduction on the right knee might point to a stronger or more dominant leg, which is responsible for generating more upward force during the jump.

Left ankle (49°) and Right ankle (58°): The plantar flexion angles show that the ankles are positioned for pushing off the ground. The higher plantar flexion in the right ankle could suggest a stronger push-off from the right foot, which is consistent with the observed asymmetries in the knee and hip.

A pre-jump ground contact time of 0.73 seconds is within the typical range for volleyball players preparing for a vertical jump. This duration reflects the time the athlete spends in preparation before liftoff, balancing stability and force production.

There is a noticeable asymmetry in the elbow, knee, and ankle joint angles. While minor asymmetries are common in sports, especially in volleyball where dominant sides develop, consistent training focusing on bilateral strength and mobility could reduce the risk of injury and enhance performance.

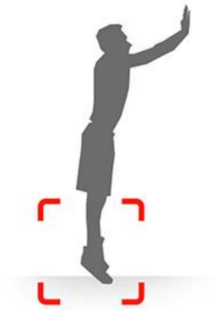
The degree of knee flexion (120°-127°) is ideal for generating explosive power during the vertical jump. Ensuring that both legs contribute equally to the push-off phase might improve jump height and overall performance.

The high plantar flexion angle (especially 58° on the right foot) indicates good push-off mechanics, which are critical for maximizing vertical jump height. Any training aimed at improving ankle strength and flexibility could further enhance this aspect.

Table-4

Lift-off position kinematics of volleyball players

№	Local joint angles	Left	Right	

1	Elbow flexion/extension (+/-)	103 º	101 º	
2	Shoulder flexion/extension (+/-)	87 º	91 º	
3	Hip flexion/extension (+/-)	17 º	16 º	
4	Knee flexion/extension (+/-)	45 º	46 º	
5	Knee internal/external rotation (+/-)	9 º	23 º	
6	Knee abduction/adduction (+/-)	-10 º	-5 º	
7	Plantar flexion/dorsiflexion (+/-)	9 º	14 º	
	Event parameters			
1	Tibial tilt at lift-off:	-31 º	31 º	
2	Vertical lift-off speed:	2.88 m/s		
3	Vertical lift-off impulse:	233 Ns		
4	Vertical lift-off force:	1667 N		
5	Kinetic energy at lift-off:	249 J		

Left elbow (103°) and Right elbow (101°): The elbows are moderately flexed, showing that the arms are actively engaged in the lift-off phase. This flexion helps players generate momentum through arm swing, which complements the upward force generated by the legs. The symmetry between both elbows suggests balanced arm movement during the take-off.

Volleyball players' left shoulder (87°) and right shoulder (91°). During lift-off, there is a noticeable flexion of both shoulders, suggesting that the player pro-pels themselves using their arms. Right-sided volleyball players typically rely on their dominant arm for serving or spiking, therefore the modest asymmetry (right shoulder flexed more than left) may imply a stronger or more dominant arm swing on the right side.

The left hip (17°) and right hip (16°) of volleyball players: It is normal for the hips to be somewhat extended during liftoff. This posture aids with balance and starts the body's upward motion. The nearly exact angles formed by the two hips demonstrate good lower body coordination.

Left knee (45°) and Right knee (46°): Both knees are flexed at similar angles, providing the primary force for pushing off the ground. This position suggests that the player is well-prepared to generate maximum force through the legs. The minimal asymmetry between the knees highlights balanced lower limb mechanics.

Left knee (9°) and Right knee (23°): The right knee shows more external rotation compared to the left. This discrepancy may indicate a natural preference or compensation in leg movement. In volleyball, slight asymmetries in leg rotation during take-off can be common due to frequent lateral movements during play.

Left knee (-10°) and Right knee (-5°): The negative values indicate slight knee adduction, meaning the knees are moving toward the midline during lift-off. This positioning can be a natural alignment for athletes preparing for a vertical leap, allowing for better stability.

Left ankle (9°) and Right ankle (14°): Both feet are in slight plantar flexion at lift-off, with the toes pointing downward. This plantar flexion contributes to pushing off the ground, generating the final boost needed for take-off. The slight difference between left and right ankles is typical and does not pose any significant concern unless exaggerated.

Left tibial tilt (-31°) and Right tibial tilt (31°): The tibial tilt at lift-off is quite significant and opposite in direction for each leg. The left tibia shows a forward tilt (negative value), while the right tibia shows a backward tilt. This imbalance might reflect a functional asymmetry in the player’s jumping technique, potentially caused by differences in leg strength or foot positioning. Correcting this through targeted strength and technique training could improve performance and reduce injury risk.

This speed is a crucial factor in determining the height the player will achieve during the jump. A speed of 2.88 m/s is relatively high for vertical jumps, reflecting the athlete’s explosive power during lift-off.

Impulse is the product of force applied over time and is critical for creating momentum. A vertical lift-off impulse of 233 Ns indicates a strong force generation during the jump, which aligns with the high lift-off speed.

This force value is the total amount of vertical force generated by the athlete’s legs during lift-off. A force of 1667 N reflects a powerful push-off, critical for maximizing vertical jump height. It highlights the athlete’s ability to generate substantial force relative to their body mass.

The kinetic energy value indicates how much energy is available for the jump. At 249 Joules, this amount of energy shows that the athlete has efficiently converted their muscular force into kinetic energy, contributing to a successful vertical leap.

The mean elbow flexion (~111°) suggests that during the flight phase, the arms remain flexed to assist in maintaining balance and preparing for the landing phase. The similarity between both arms in their minimum and maximum values indicates symmetrical upper-body coordination. Arm swing during the take-off phase significantly contributes to jump height.

The shoulder flexion increases as the arms swing upwards during the flight phase. The significant range between minimum and maximum values shows dynamic arm movement. The slight asymmetry (right shoulder reaching 94° compared to 88° on the left) might suggest a dominant arm contributing more to the upward force, a common occurrence in volleyball players due to the repetitive nature of spiking and serving (Table-5).

Table-5

Flight phase kinematics of volleyball players

№	Local joint angles	Left			Right		
		Min	Mean	Max	Min	Mean	Max
1	Elbow flexion/extension (+/-)	103 º	111 º	115 º	101 º	111 º	116 º
2	Shoulder flexion/extension (+/-)	32 º	48 º	88 º	22 º	42 º	94 º
3	Hip flexion/extension (+/-)	-1 º	3 º	17 º	-4 º	2 º	16 º
4	Knee flexion/extension (+/-)	-4 º	3 º	45 º	-1 º	5 º	46 º
5	Knee internal/external rotation (+/-)	-12 º	-9 º	9 º	1 º	5 º	23 º
6	Knee abduction/adduction (+/-)	-10 º	-3 º	-1 º	-5 º	-1 º	0 º
7	Plantar flexion/dorsiflexion (+/-)	-39 º	-32 º	9 º	-37 º	-29 º	14 º
	Phase parameters						
1	Flight duration:	0.62 s					
2	Flight height:	540 mm					
3	COG horizontal displacement:	78 mm					
4	Feet horizontal displacement:	120 mm	146 mm				

The hips are nearly neutral at the beginning of the flight phase (mean around 2°-3°) but flex slightly as the jump progresses. This slight flexion helps with stabilizing the body mid-air. The minimal difference between the left and right hips indicates balanced lower body coordination during the jump.

The knees start in near-full extension (negative values), then flex during the flight phase. The significant maximum flexion (45°-46°) shows the preparation for the landing phase as the legs begin to flex before ground contact. The slight asymmetry in the knees is minimal, indicating relatively balanced leg movement.

There is a larger range of internal/external rotation in the right knee compared to the left, possibly indicating a dominant leg or differences in muscle coordination. The external rotation in the right knee is typical for players preparing for a stable landing.

Both knees exhibit slight adduction (negative values) during the flight phase. This could be due to the legs coming together in preparation for landing, a common biomechanical pattern seen in jumping sports.

Left (-39° to 9°) and Right (-37° to 14°): The large plantar flexion (negative values) indicates that the toes are pointed downward during the flight phase. This is typical in vertical jumps, where plantar flexion occurs at the peak of the jump. The slight asymmetry between the left and right ankles suggests that the right foot may be contributing more to propulsion or control in the air.

A flight time of 0.62 seconds is consistent with high-performance volleyball players during a vertical jump. This value reflects the duration in the air after the take-off phase and is crucial for evaluating jump efficiency.

A flight height of 540 mm (54 cm) is indicative of a strong vertical leap. For a volleyball player, this height provides enough clearance to perform spiking or blocking maneuvers effectively.

The horizontal displacement of the center of gravity (78 mm) suggests minimal forward or backward movement during the jump. This is desirable, as volleyball players aim for a vertical jump rather than a broad jump during game situations like blocking or spiking.

Feet Horizontal Displacement (Left: 120 mm, Right: 146 mm): The difference in horizontal displacement between the feet suggests a slight asymmetry in how the legs push off during the jump. The right foot has more horizontal movement, which could indicate a slight imbalance in force application. Corrective training to improve bilateral power distribution might help achieve more symmetry and efficient jumping mechanics.

Table-6

Landing phase kinematics of volleyball players

№	Local joint angles	Left			Right		
		Min	Mean	Max	Min	Mean	Max

1	Elbow flexion/extension (+/-)	93 º	100 º	115 º	99 º	104 º	116 º
2	Shoulder flexion/extension (+/-)	23 º	27 º	32 º	23 º	26 º	30 º
3	Hip flexion/extension (+/-)	3 º	13 º	21 º	3 º	13 º	22 º
4	Knee flexion/extension (+/-)	17 º	50 º	72 º	19 º	52 º	78 º
5	Knee internal/external rotation (+/-)	1 º	13 º	21 º	13 º	24 º	31 º
6	Knee abduction/adduction (+/-)	-15 º	-11 º	-7 º	-6 º	-2 º	3 º
7	Plantar flexion/dorsiflexion (+/-)	-19 º	18 º	39 º	-16 º	22 º	43 º
	Phase parameters						
1	Landing duration:	0.46 s					
2	Preparation to landing height difference:	230 mm					
	Max. pressure at the ball of the foot:	- Pa	- Pa				

Both the right elbow (99°-116°) and the left elbow (93°-115°). The elbows maintain a moderate flexion during the landing phase, with the right elbow exhib-iting a somewhat larger range of flexion. Flexion of this kind stabilizes the upper body and absorbs impact forces. Effective usage of the arms upon landing is demonstrated by the elbow symmetry (Table-6).

Shoulder flexion and extension. Both the right and left shoulders (23°–32° and 23°–30°). Relative to their active contributions to the landing mechanics, both shoulders move very little during landing, suggesting that they are stable. To aid with upper-body control and balance during the collision, the shoulders retain a nearly symmetric flexion.

3°–21° on the left hip and 3°–22° on the right hip. During landing, the hips flex slightly—by around 13° on average. By bringing the body's center of gravity down and putting it in a stable posture, this degree of flexion enables the hips to assist in absorbing landing forces. Perfect for balanced landing mechanics is the symmetrical hip movement.

Left knee (17°-72°) and Right knee (19°-78°). Both knees exhibit a large range of flexion, which is crucial for absorbing the forces generated during landing. The mean flexion around 50°-52° indicates that the player uses their knees effectively to cushion the landing impact. The greater flexion on the right knee might suggest a slight asymmetry in how the legs are absorbing the force, but this is relatively normal.

Left knee (1°-21°) and Right knee (13°-31°). The right knee shows more internal/external rotation compared to the left knee. This could be due to a natural asymmetry in the player's movement or a possible compensation for the dominant leg during landing. Careful attention should be paid to this rotation to ensure it does not lead to excessive stress on the knee joint over time.

Left knee (-15° to -7°) and Right knee (-6° to 3°). The left knee is more abducted (moving away from the midline) than the right knee. This difference in abduction/adduction angles suggests that the left leg may be experiencing greater lateral forces during landing. Over time, this could increase the risk of knee injuries such as ACL tears if not addressed with proper training.

Left ankle (-19° to 39°) and Right ankle (-16° to 43°). The plantar flexion/dorsiflexion shows that the ankles are actively involved in landing, with dorsiflexion occurring to stabilize the foot upon ground contact. The right ankle shows slightly more dorsiflexion, indicating a stronger or more controlled landing on that side. The dorsiflexion helps with shock absorption and stability during landing.

Landing Duration (0.46 s). A landing duration of 0.46 seconds suggests that the player absorbs the landing impact over a relatively short time. Volleyball players generally need to land quickly to prepare for subsequent movements, so this duration indicates efficient impact absorption.

Preparation to Landing Height Difference (230 mm). The 230 mm height difference between the preparation and landing phases indicates the vertical distance covered during the descent from the jump. This difference provides context for the forces that need to be absorbed during landing, and the proper kinematic adjustments (such as knee flexion) help manage this height difference.

Max. Pressure at the Ball of the Foot. Although the exact pressure values are missing ("-Pa"), the pressure at the ball of the foot is crucial for understanding how the body distributes force during landing. High pressure at the ball of the foot can indicate effective force transfer but should be monitored to prevent excessive stress on the foot and lower leg.

In conclusion, the kinematic analysis of the vertical jump in volleyball players offers crucial insights into their performance during different phases of the jump, including the preparation, lift-off, flight, and landing. Key observations include:

1. Upper and Lower Body Coordination: Both arms and legs exhibit slight asymmetry in joint angles, such as elbow and knee flexion, which is natural given the dominant side usage in

volleyball. However, enhancing bilateral strength and coordination can minimize these differences, potentially improving overall performance.

2. Effective Force Production: The players demonstrate strong vertical lift-off speed (2.88 m/s) and vertical force generation (1667 N), which are indicative of their explosive power. This is critical for achieving higher jumps, with the athlete in this case reaching a peak height of 540 mm.

3. Landing Mechanics: The knee and ankle flexion during landing indicate effective shock absorption, but some asymmetry in knee internal/external rotation and adduction could increase the risk of injury over time. Proper strength and stability training for the lower limbs is recommended to ensure safe landings and long-term joint health.

4. Kinematic Performance: The 3D motion analysis data reveals the detailed biomechanical factors contributing to vertical jump success, highlighting areas where players can improve their force distribution, posture, and overall efficiency during the jump.

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