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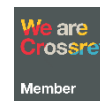
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Biomechanical determinants of volleyball smash performance in physical education: a comprehensive literature review

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ABSTRACT

Smash performance in volleyball is a complex motor skill influenced by lower-limb explosive power, hand-eye coordination, and trunk flexibility. This systematic literature review (2018–2025) synthesized 15 studies from international and national databases using PRISMA guidelines. Findings indicate that explosive leg strength drives take-off height, angle of attack, and initial momentum, with rate of force development and coordination patterns mediating mid-air stability. Hand-eye coordination critically supports timing accuracy and directional control, while trunk flexibility enables efficient energy transfer and arm acceleration. Effective smash execution emerges from the interaction of force production, neurosensory control, and segmental mobility. Training programs should adopt multidimensional approaches integrating plyometrics, visual-motor drills, and flexibility exercises, tailored to developmental stage and individual needs, with assessments guiding prioritization. Future research should evaluate combined interventions and performance transfer in competitive settings.



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Introduction

The smash is widely recognized as the most decisive component in modern volleyball offensive strategies, as it directly contributes to scoring and provides a competitive advantage. Effective smash execution requires not only physical strength but also precise timing, coordinated movement, and technical proficiency. Consequently, understanding the biomechanical determinants underlying smash performance is essential for optimizing athlete development, enhancing technical effectiveness, and informing evidence-based training programs. Previous biomechanical investigations have consistently emphasized the role of lower-limb explosive power in achieving optimal jump height, take-off velocity, and advantageous hitting positions, highlighting the importance of proximal-to-distal sequencing within the kinetic chain (Edmizal et al., 2024; Guntur et al., 2022; Nolasco et al., 2022).

Hand–eye coordination is another critical component that determines timing accuracy and the ability to adjust movements in response to ball trajectory. Research has shown that athletes with superior visual-motor skills are more likely to achieve optimal ball contact points and maintain accuracy under variable game conditions (Kishita et al., 2020; Ren et al., 2025). Similarly, trunk flexibility, particularly lumbar and thoracic mobility, facilitates effective trunk rotation and extension, allowing energy produced by the lower limbs to be efficiently transferred to the upper body during the arm swing (Kumar & Zemkov, 2022; Mocanu & Dobrescu, 2021; Myrick et al., 2019). The integration of these factors lower-limb power, hand–eye coordination, and trunk flexibility is therefore essential to produce high ball velocity and consistent accuracy in smash execution.

Despite the well-established theoretical framework, empirical evidence indicates that adolescent and non-elite athletes frequently demonstrate suboptimal smash performance. Timing errors are often observed due to inadequate hand–eye coordination (Szabo et al., 2021; Trongjitpituk, 2024), while studies in Indonesia report that lower-limb explosive power among middle-school volleyball players is typically moderate-to-low, limiting jump height and reducing smash effectiveness (Kamadi et al., 2023; Marpaung & Priyonoadi, 2020; Sistiasih et al., 2024). In addition, approximately 70% of young athletes demonstrate low smash accuracy due to poor integration between jump mechanics and visual tracking (Hakim et al., 2024; Putra et al., 2024). These technical limitations are often compounded by training programs that inadequately address the combined development of these biomechanical components.

The educational context of school-aged athletes further highlights the importance of biomechanical understanding. Physical capacities, coordination abilities, and movement patterns are still developing during adolescence, rendering these athletes highly adaptable to targeted interventions. Identifying and emphasizing key biomechanical determinants allows physical education teachers and youth coaches to design developmentally appropriate learning activities that focus on movement quality, correct sequencing, and injury prevention rather than solely on performance outcomes. A process-oriented, biomechanically informed instructional approach promotes long-term athletic development and supports safer, more effective skill acquisition.

Previous studies have predominantly examined individual variables in isolation, such as lower-limb strength, hand–eye coordination, or flexibility, without sufficiently addressing the complex interactions that occur during multi-segmental skill execution (Fuchs et al., 2019; Afonso et al., 2021; Oliveira & Alfano, 2020). The lack of integrative analysis limits understanding of how these factors collectively contribute to smash performance and reduces the applicability of findings to practical training settings. Moreover, prior reviews rarely translate biomechanical insights into concrete recommendations for school-based or club-level programs, leaving a gap between scientific knowledge and applied practice.

To address these gaps, this review synthesizes current empirical evidence on the three primary biomechanical determinants of volleyball smash performance: lower-limb explosive power, hand–eye coordination, and trunk flexibility. It aims to elucidate how these components interact to produce efficient and effective smash execution while identifying patterns and discrepancies across national and international studies. The findings are intended to provide coaches, physical education practitioners, and sport scientists with a comprehensive, evidence-based foundation for designing training programs that reflect both developmental considerations and competitive demands. Ultimately, this review seeks to enhance scientific understanding and practical implementation of volleyball smash techniques across diverse educational and competitive contexts.

Method

This study adopted a systematic literature review methodology developed in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, rigor, and replicability throughout the review process. The literature search was conducted using major international and national scientific databases, targeting peer-reviewed studies published between 2018 and 2025. A structured search strategy was applied using Boolean operators with key terms including “volleyball smash performance,” “biomechanics of spike,” “lower-limb

explosive power,” “hand–eye coordination,” and “trunk flexibility.” Only journal articles published in English or Indonesian that explicitly examined biomechanical determinants of volleyball smash performance were considered eligible for inclusion.

The article selection process involved several stages. Initially, all potentially relevant records identified through database searching were compiled, and duplicate entries were removed. Subsequently, titles and abstracts were screened to assess their relevance to the scope of the review. Articles that met the preliminary criteria underwent full-text evaluation based on predefined inclusion standards: (1) studies involving volleyball players or athletes, (2) investigations examining at least one of the biomechanical variables lower-limb explosive power, hand–eye coordination, or trunk flexibility and (3) empirical or review studies presenting clearly defined methodologies and measurable biomechanical outcomes. Studies were excluded if they (1) did not focus on volleyball smash techniques, (2) involved non-volleyball or non-athletic populations, or (3) failed to report quantifiable biomechanical indicators.

Data extraction was carried out systematically by recording key information from each eligible article, including authorship, year of publication, research design, participant characteristics, measurement instruments, variables analyzed, and principal findings related to smash performance. The extracted data were synthesized using a narrative synthesis approach, enabling comparison across studies, identification of dominant biomechanical determinants, and evaluation of methodological trends and inconsistencies within the literature. To enhance the validity and robustness of the review, findings were cross-checked across multiple sources to ensure consistency of evidence, particularly between international and national studies. Through this methodological framework, the review provides a comprehensive and evidence-based understanding of the interaction among lower-limb explosive power, hand–eye coordination, and trunk flexibility in influencing volleyball smash performance.

Results and Discussions

The initial literature search identified 145 articles related to volleyball biomechanics and smash performance. Following the removal of 37 duplicate records, 108 articles remained for the screening process. Title and abstract screening led to the exclusion of 72 articles that were not directly related to the biomechanical determinants of volleyball smash performance. The remaining 36 articles were subjected to full-text eligibility assessment, during which 21 studies were excluded because they did not include biomechanical measurements or did not specifically analyze smash performance. Ultimately, 15 studies met the predefined inclusion criteria and were included in this review.

The selected studies were classified into two primary biomechanical themes: (1) lower-limb explosive power and (2) upper-body control mechanisms, which include hand–eye coordination and trunk flexibility. The synthesized findings for each theme are presented below.

Lower-Limb Explosive Power and Smash Performance

The synthesis of the reviewed literature indicates that lower-limb explosive power is the most frequently reported biomechanical factor directly influencing smash performance. Most studies consistently demonstrate that greater leg muscle explosiveness is positively associated with increased jump height, allowing athletes to achieve a more advantageous hitting position. Higher take-off height, in turn, facilitates a steeper angle of attack and contributes to greater smash velocity.

Both international and national studies report that athletes with superior vertical jump performance tend to generate higher ball speeds during smashes. These findings highlight the role of the lower limbs as the primary source of propulsive force within the kinetic chain, providing the initial energy that is subsequently transferred to upper-body movements. Across the reviewed studies, a variety of assessment methods—such as squat jumps (SJ), countermovement jumps (CMJ), and force plate analyses—were employed, all of which consistently revealed a positive relationship between leg muscle power and smash performance. Collectively, these findings support the conclusion that lower-limb explosive power constitutes a fundamental biomechanical determinant of effective smash execution.

Table 1. Summary of Studies Examining Lower-Limb Power and Smash Performance

Study	Sample	Measurement Tools	Key Findings
Tai et al. (2021)	20 youth athletes	Vertical Jump, Spike Radar	Greater leg power significantly increases smash velocity
Trecroci et al. (2021)	28 junior players	CMJ, Skill Test	Improved leg strength enhances timing and smash accuracy
Aldani et al. (2021)	34 students	SJ & CMJ	Positive correlation between leg power and smash ability

Interpretation of Table 1 indicates strong consistency across studies regarding the contribution of leg muscle explosiveness to smash success. Despite differences in research design and measurement instruments, all studies conclude that improvements in jump performance directly enhance smash effectiveness. Increased lower-limb explosiveness enables athletes to jump higher, improve body positioning, and optimize the angle of attack, resulting in greater impact force at ball contact. Furthermore, Trecroci et al. (2021) reported that leg strength also contributes to post-take-off body stability, which is essential for maintaining control during follow-through movements. National-level evidence provided by Aldani et al. (2021) reinforces these findings by emphasizing the importance of fundamental physical capacities, such as leg strength and reaction ability, in maximizing smash performance among students. Overall, the evidence demonstrates robust agreement across contexts, confirming lower-limb explosive power as the biomechanical foundation of the smash movement.

Hand–Eye Coordination and Trunk Flexibility in Smash Accuracy

The reviewed literature also emphasizes the critical role of hand–eye coordination and trunk flexibility in achieving accurate and controlled smash execution. Hand–eye coordination is consistently identified as a key factor influencing timing precision, particularly in adjusting body and arm movements to the ball's trajectory. International studies report that athletes with superior visual-motor coordination demonstrate more consistent ball contact and higher hitting accuracy compared to less skilled players.

Trunk (lumbar) flexibility has similarly been shown to facilitate effective upper-body rotation and extension, thereby enhancing energy transfer during the arm swing phase. Several national and international studies indicate that greater trunk flexibility is associated with improved smash power and directional accuracy. These findings suggest that, in addition to lower-limb explosiveness, both hand–eye coordination and trunk flexibility represent essential biomechanical determinants of smash performance.

Table 2. Summary of Studies on Hand–Eye Coordination and Trunk Flexibility

Study	Focus Variable	Measurement Tools	Key Findings
Kishita et al. (2020)	Hand–eye coordination	Visual Tracking Test	Visual coordination strongly influences timing and smash precision
Palmer & McCabe (2023)	Trunk flexibility	Trunk Mobility Test	Flexibility enhances kinetic chain efficiency during smash
Oktadinata & Prabowo (2025)	Coordination & flexibility	Coordination Test	Poor coordination reduces accuracy and directional control

The synthesis of findings in Table 2 demonstrates that hand–eye coordination plays a central role in determining ball contact accuracy, particularly during the ball-tracking phase preceding impact. Kishita et al. (2020) showed that athletes with higher visual coordination capacities are better able to adapt their movements to changes in ball trajectory. Trunk flexibility also contributes significantly by supporting the rotational and extension movements necessary for a powerful and efficient arm swing (Palmer & McCabe, 2023). At the national level, Oktadinata and Prabowo (2025) confirmed that deficiencies in visual-motor coordination are closely associated with reduced smash accuracy, especially among adolescent players. These findings indicate that hand–eye coordination and trunk flexibility not only affect technical execution but also influence body stability and energy transfer efficiency during the smash.

The findings of this review confirm that lower-limb explosive power is a primary determinant of volleyball smash performance. Explosive leg strength regulates take-off height, angle of attack, and initial momentum, all of which significantly influence smash velocity. From a biomechanical perspective, rapid force production in the lower extremities generates an impulse that is transferred through the kinetic chain via proximal-to-distal sequencing, ultimately achieving maximal velocity at the hitting arm (Almansoof et al., 2023; Sarvestan et al., 2020). Kinematic and coordination-based analyses consistently identify this sequencing as a critical contributor to effective smash execution, highlighting that both the magnitude and timing of force production are essential.

Empirical evidence from correlational and experimental studies demonstrates that vertical jump performance, measured using SJ and CMJ protocols, is strongly associated with smash velocity outcomes (Akdoğan et al., 2022; Washif & Kok, 2021). However, force-time analyses further suggest that evaluating rate of force development (RFD) provides a more complete understanding of explosive capacity, as higher RFD enhances mid-air stability and accuracy at high movement speeds (Arafat, 2024; Farajijalal et al., 2025; Wang et al., 2025). These results indicate that lower-limb power alone is insufficient to explain performance differences; coordination patterns and timing of force application are equally crucial for effective energy transfer and optimal smash execution.

Hand-eye coordination emerges as a critical determinant of timing accuracy and directional control. Superior visual-motor abilities allow athletes to rapidly adjust to variations in ball trajectory and external constraints such as opponent blocking, thereby increasing the likelihood of effective, difficult-to-return smashes (Cardoso et al., 2020; Piva et al., 2025). National-level studies further support this relationship, showing that deficiencies in visual-motor coordination among young athletes are strongly linked to reduced smash accuracy during competitive play (Sin et al., 2020; Sistiasih et al., 2024). These findings underscore that sensorimotor control determines the extent to which mechanical potential from explosive power can be translated into functional performance during match situations.

Trunk flexibility also plays a central role in efficient smash execution. Adequate lumbar and thoracic mobility facilitates trunk rotation and extension, enabling effective energy transfer from lower limbs to upper extremities. Three-dimensional kinematic analyses demonstrate that greater trunk range of motion enhances arm acceleration and hand-tip velocity at ball contact (Salamanca, 2024; Santos-Paz et al., 2022; Costanzo et al., 2019; Liu & Billard, 2025; Zhou et al., 2025). Conversely, limited trunk flexibility can result in compensatory movement patterns that reduce energy transfer efficiency, compromise accuracy, and increase the risk of overuse injuries. Integrating these findings with evidence on explosive power and coordination reinforces the view that smash performance is the product of interacting components involving force production, neurosensory control, and segmental mobility (Pratama, 2020).

From a practical standpoint, these results highlight the need for multidimensional training programs that target all three domains simultaneously. Lower-limb explosive power can be developed through structured plyometric exercises and force-velocity profiling, while hand-eye coordination can be enhanced using visual tracking drills and reactive tasks. Trunk mobility training should focus on systematic flexibility and rotational exercises. Coaches and physical education practitioners should assess baseline capabilities across all three areas to prioritize individualized interventions. Training progression must also be developmentally appropriate, particularly for school-aged athletes, to ensure safe and effective skill acquisition.

Finally, future research should examine combined, medium-term interventions that integrate strength, coordination, and flexibility training to evaluate their impact on both technical skill and competitive performance. Greater emphasis on the interaction between biomechanical determinants, rather than isolated factors, will improve understanding of how to optimize smash execution in diverse athlete populations and enhance evidence-based coaching strategies. By linking biomechanical insights with practical applications, this review contributes to advancing volleyball training methodology at both educational and competitive levels.

Conclusions

Based on the findings of this comprehensive literature review, the performance of a volleyball smash is strongly influenced by three primary biomechanical determinants: lower-limb explosive power, hand–eye coordination, and trunk flexibility. Lower-limb explosive power consistently emerged as the most dominant factor, as it directly affects take-off height, aerial stability, and striking force generation. Meanwhile, hand–eye coordination plays a critical role in timing, ball-tracking, and the precision of contact, ensuring that athletes can adapt to variations in ball trajectory and defensive pressure. Trunk flexibility contributes significantly to the efficiency of kinetic-chain energy transfer, enabling more powerful and controlled arm swings. Collectively, the synthesis of 15 eligible studies demonstrates that smash performance cannot be optimized by focusing on a single component; instead, it requires an integrated interplay of mechanical power, neuromuscular control, and segmental mobility. Therefore, the evidence strongly supports the need for multidimensional training programs that target all three determinants simultaneously.

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