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The Importance of Landing Biomechanics in Injury Prevention in Artistic Gymnastics: A Systematic Review

Zulbahri[1], Rully Effendi[2], Liliana Puspa Sari[3], Ika Endah Puspita Sari[4], Andra Rizky Putra[5], Randi Kurniawan[6], Abdul Aziz Purnomo Shidiq[7]

[1]Department of Physical Education and Sport, Faculty of Sports Science, Universitas Negeri Padang, Indonesia
[2.5]Sport Science, STOK Bina Guna Medan, Indonesia
[3.4]Physical Education, STOK Bina Guna, Medan, Indonesia
[6]Sport Science, Faculty of Sport Science, State University of Medan, Indonesia
[7]Department of Physical Education Health and Recreation, Faculty of Sport Science, Universitas Sebelas Maret, Indonesia

Correspondence:
Zulbahri
Department of Physical Education and Sport, Faculty of Sports Science, Universitas Negeri Padang, Indonesia, zulbahri@fik.unp.ac.id

Abstract: *Landing movements in floor gymnastics expose athletes to high mechanical loads that substantially increase the risk of lower extremity injuries. Biomechanical analysis has been widely used to identify risk factors associated with injury; however, the available evidence remains fragmented, with inconsistent findings across kinematic, kinetic, and neuromuscular parameters. A comprehensive synthesis of biomechanical landing characteristics specific to floor gymnastics is lacking. This systematic literature review aimed to synthesize biomechanical evidence on landing mechanics in floor gymnastics and to identify key biomechanical factors associated with injury risk to inform injury prevention strategies. A systematic search was conducted in Scopus, Web of Science, PubMed, and SPORTDiscus following PRISMA guidelines. Peer-reviewed studies examining biomechanical aspects of landings in floor gymnastics were included. Extracted data were categorized into kinematic, kinetic, and neuromuscular variables, and methodological quality was assessed using a standardized assessment tool. The reviewed studies consistently identified high vertical ground reaction forces, excessive knee valgus angle, reduced hip and knee flexion, and inadequate eccentric control during landing as key biomechanical risk factors for injury. However, substantial heterogeneity in landing tasks, measurement protocols, and analytical methods limits comparisons between studies. Few studies examined multi-joint interactions or directly linked biomechanical findings to injury prevention interventions.* ***Conclusions.*** *This review provides the first integrated synthesis of landing biomechanics specific to floor gymnastics by mapping kinematic-kinetic risk factors and highlighting the absence of a standardized assessment framework and intervention-oriented research. Biomechanical analysis is crucial for understanding injury mechanisms in floor gymnastics landings. Future research should adopt standardized multidimensional biomechanical models and longitudinal or intervention-based designs to translate biomechanical evidence into effective injury prevention programs.*

Keywords: *Floor Gymnastics, Landing Biomechanics, Injury Prevention, Systematic Literature Review*

Introduction

Floor gymnastics is a very demanding sport, characterized by complex acrobatic sequences that require athletes to perform repeated jumping, rolling, and landing movements under great mechanical loads (Abouzeid et al., 2026). These movements place high impact forces on the musculoskeletal system (Malisoux et al., 2023), especially during the landing phase, which has been identified as a critical moment associated with an increased risk of injury (Chou et al., 2023). It is consistently reported that lower extremity injuries particularly those affecting the ankles, knees and hips are among the most common in gymnastics, with many injuries occurring during or immediately after landing from aerial moves (Skopal et al., 2020). Repeated exposure to high ground reaction forces, combined with rapid joint loading rates and limited recovery time, underscores the importance of understanding landing biomechanics as a key component of injury prevention in floor gymnastics.

From a biomechanical perspective, landing is a complex motor task that requires coordinated energy absorption across multiple joints to reduce external forces (Chen et al., 2025). An effective landing strategy typically involves adequate hip, knee, and ankle flexion, appropriate modulation of joint stiffness, and a timely neuromuscular activation pattern. Conversely, suboptimal landing mechanics such as reduced lower leg flexion, excessive knee valgus, asymmetric loading, and poor eccentric muscle control have been associated with increased mechanical stress on passive joint structures (Bocheng et al., 2024). In gymnastics, where athletes are frequently exposed to high-impact

landings after performing movements such as acrobatic passes and landings, these maladaptive movement patterns can contribute to acute traumatic injuries and the development of overuse conditions (Bonazza et al., 2022).

Over the past two decades, biomechanical analysis has become an important methodological approach for investigating landing mechanics in gymnastics. Advances in motion capture systems, force platforms, and electromyography have enabled researchers to measure kinematic, kinetic, and neuromuscular variables associated with landing performance. Many studies have reported associations between specific biomechanical parameters such as high vertical ground reaction forces, increased knee abduction moments, delayed muscle activation, and reduced energy absorption at the proximal joints and increased injury risk (Hu et al., 2022). These findings have provided valuable insights into the mechanical factors underlying common gymnastics-related injuries, including anterior cruciate ligament (ACL) injuries, ankle sprains, and stress-related pathologies (Thomas & Thomas, 2019). Although the volume of biomechanical research in gymnastics is increasing, the current evidence relating specifically to gymnastics floor landings remains fragmented and lacks systematic integration (Ahsan & Alzahrani, 2024). Individual studies often differ significantly in terms of participant characteristics (age, gender, skill level), experimental protocols (landing height, task constraints), and measurement techniques. This heterogeneity complicates comparisons between studies and limits the ability to draw robust conclusions regarding key biomechanical risk factors. Furthermore, many studies focus on isolated variables or single-joint analyses, which may fail to capture the multi-joint coordination and dynamic interactions that characterize real-world landings in floor gymnastics (L. Li et al., 2025).

In recent years, systematic literature reviews have emerged as a valuable tool for synthesizing biomechanical evidence and identifying research trends, methodological strengths, and limitations in a particular domain (Zhou et al., 2025). However, existing reviews of gymnastics-related injury research often adopt a broad focus encompassing a variety of devices or injury types, thus providing limited insight into the biomechanics of landings specific to floor gymnastics. To date, no systematic review has comprehensively synthesized biomechanical evidence on landing mechanics in floor gymnastics while explicitly addressing methodological heterogeneity, biomechanical risk factors, and implications for injury prevention. This gap represents a significant limitation in the current understanding of injury mechanisms in this sport. Addressing this gap is crucial given the increasing emphasis on evidence-based injury prevention in elite and youth gymnastics. A systematic synthesis of biomechanical findings can help identify consistent risk factors, highlight methodological shortcomings, and inform future research directions. Furthermore, by critically evaluating the extent to which existing studies integrate kinematic, kinetic, and neuromuscular perspectives, such a review could contribute to the development of a more comprehensive model of landing biomechanics in floor gymnastics.

Therefore, the purpose of this systematic literature review is to critically synthesize the biomechanical evidence related to landing mechanics in floor gymnastics and to identify key biomechanical determinants associated with injury risk. Specifically, this review aims to (1) summarize the kinematic, kinetic, and neuromuscular characteristics of floor gymnastics landings, (2) evaluate the methodological quality and sources of heterogeneity across studies, and (3) identify research gaps related to standardization and application in injury prevention. By addressing these objectives, this review seeks to provide a strong theoretical foundation for future biomechanical research and to support the development of effective, evidence-based injury prevention strategies in floor gymnastics.

Materials And Methods

Study Design and Reporting Framework

This study used a systematic literature review design to synthesize existing biomechanical evidence related to landing mechanics and injury prevention in floor gymnastics. The review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure methodological rigor, transparency, and reproducibility. The protocol was developed to address the lack of standardized synthesis in previous gymnastics-related biomechanical research, which often reports fragmented findings without systematic integration.

Search Strategy

A comprehensive literature search was conducted in four major electronic databases: Scopus, Web of Science, PubMed, and SPORTDiscus. These databases were selected to encompass multidisciplinary research spanning bio-

mechanics, sports science, and injury prevention. The search strategy incorporated controlled vocabulary and free-text terms related to gymnastics, landing biomechanics, and injury risk. Primary search terms included combinations of: "floor gymnastics," "landing," "biomechanics," "kinematics," "kinetics," "ground reaction force," "injury," and "injury prevention." Boolean operators (AND/OR) were applied to narrow the search. Reference lists of included studies were also manually reviewed to identify additional relevant articles. This broad yet targeted strategy was designed to address key gaps in previous reviews, which often relied on limited databases or narrow search terms.

Eligibility Criteria

Studies were included if: (1) they were peer-reviewed journal articles published in English; (2) they involved participants performing landing tasks relevant to floor gymnastics; (3) they reported biomechanical outcomes related to landings, including kinematic, kinetic, and/or neuromuscular variables; and (4) they examined injury risk factors or implications for injury prevention. Studies focusing exclusively on non-floor apparatus, case reports, conference proceedings, and non-biomechanical analyses were excluded. Eligibility criteria were established to address the lack of specificity observed in previous reviews that combined heterogeneous gymnastics disciplines without differentiating landing demands.

Study Selection

All identified records were imported into reference management software, and duplicates were removed. Titles and abstracts were independently screened by two reviewers to assess relevance based on the inclusion criteria. Full-text articles were then reviewed to determine final eligibility. Discrepancies were resolved through discussion or consultation with a third reviewer. This multi-stage selection process aimed to minimize selection bias and enhance the reliability of the evidence synthesis, addressing methodological weaknesses identified in previous narrative reviews.

Data Extraction and Categorization

A standardized data extraction form was used to systematically collect information on study characteristics (sample size, participant level, study design), biomechanical variables, measurement instruments, and key findings. Extracted biomechanical outcomes were categorized into kinematic, kinetic, and neuromuscular domains to allow for structured comparisons across studies. This categorization was specifically adopted to address methodological gaps in the existing literature, where biomechanical findings are often reported separately without an integrative synthesis across domains.

Methodological Quality Assessment

The methodological quality of included studies was assessed using a standardized assessment tool appropriate for observational and experimental biomechanical research. Criteria included study design, measurement validity, biomechanical instrument reliability, and clarity of outcome reporting. Quality assessment was conducted independently by two reviewers, and studies were classified based on overall methodological rigor. This step was crucial in addressing the lack of quality assessment in previous reviews, which has limited the interpretation of biomechanical evidence for injury prevention.

All stages of the method in this research can be seen more clearly in Figure 1 which is presented below.

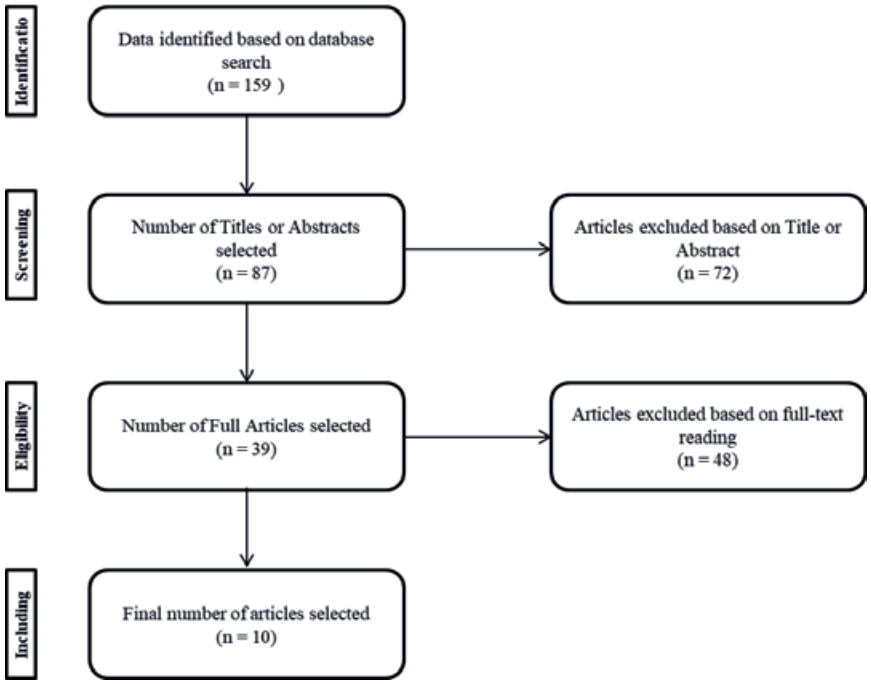


Figure 1. *PRISMA flowchart of the article selection process*

Results

The effects of biomechanical analysis of landings on injury prevention in floor gymnastics are detailed in table 1.

Table 1. *Results of the Landing Biomechanics Analysis Review for Injury Prevention in Floor Gymnastics*

No	Author (Year)	Article Title	Study Design	Subject	Key Biomechanical Variables	Key Findings Related to Injuries
1	McNitt-Gray (2021)	*Kinetics of the Lower Extremities During Drop Landings*	Experimental	Gymnast	GRF, joint moments, knee & hip flexion	Greater joint flexion decreases GRF and joint load.
2	McNitt-Gray et al. (2022)	*Landing Strategies Used by Gymnasts on Different Surfaces*	Experimental	Gymnast	Lower extremity kinetics	Landing surface and strategy influence the risk of injury.
3	Seegmiller & McCaw (2021)	*Ground Reaction Forces Among Gymnasts During Drop Landings*	Experimental	Gymnasts & non-athletes	Vertical GRF, contact time	Gymnasts show better force control
4	Gittoes & Irwin (2012)	*Biomechanical Approaches to Understanding Injurious Gymnastics Landings*	Narrative review	Gymnast	GRF, joint angle, stiffness	Stiff landings increase the risk of lower extremity injuries.
5	Christoforidou et al. (2024)	*Landing from Different Heights in Trained Gymnasts*	Experimental	Junior gymnastics athlete	Muscle activation, GRF, joint flexion	Landing from high altitude increases neuromuscular demands.
6	Straker et al. (2021)	*Biomechanical Responses to Landing Strategies of Female Artistic Gymnasts*	Experimental	Female gymnast	Knee angle, GRF, symmetry	High knee valgus is associated with a risk of knee injury
7	Mkaouer et al. (2023)	*Kinetic and Kinematic Analysis of Landing in Artistic Gymnastics*	Experimental	Elite gymnastics athlete	Joint moment, GRF, angular velocity	Arm swing technique affects landing load
8	Pavlasová et al. (2024)	*Biomechanics of Landing in Gymnasts: A Scoping Review*	Scoping review	Gymnast	Kinematic–kinetic–EMG	Lack of standard biomechanical methods in landing studies

9	Slater et al. (2025)	*Lower Limb Flexion and Impact Forces in Gymnastics Landings*	Observational	Gymnast	Knee & hip flexion, GRF	Lower extremity flexion reduces impact forces
10	Farana et al. (2023)	*Neuromuscular Control During Gymnastics Landings*	Experimental	Gymnast	EMG activation, activation time	Neuromuscular control plays an important role in injury prevention.

Discussion

This systematic review aimed to synthesize biomechanical evidence related to landing mechanics and injury prevention in floor gymnastics. Findings indicate that landing is a critical phase of gymnastics performance where athletes are exposed to substantial mechanical loading, particularly on the lower extremities. Across the included studies, consistent biomechanical patterns associated with increased injury risk were identified, reinforcing the importance of optimizing landing strategies to reduce acute and overuse injuries in floor gymnastics. One of the most consistent findings reported across studies is the association between high vertical ground reaction force (vGRF) and increased injury risk upon landing (Krause et al., 2023). High vGRF values are generally observed during stiff landing strategies characterized by limited hip, knee, and ankle flexion (Zaki et al., 2025). Such a landing pattern reduces the body's ability to dissipate impact forces through joint movement and eccentric muscle action .(Almeida et al., 2015), thereby increasing mechanical stress on passive structures such as ligaments and articular cartilage (Xu et al., 2020). These findings are consistent with established biomechanical principles showing that greater joint flexion and longer force damping times are protective against impact-related injuries (D. Li et al., 2025). In addition to vertical loads, frontal plane mechanics, particularly excessive knee valgus angle, emerge as a major biomechanical risk factor (Belkhelladi et al., 2025). Several studies have reported that increased knee valgus during landing is associated with higher knee abduction moments, which are widely recognized as a risk factor for anterior cruciate ligament (ACL) injury (Larwa et al., 2021). These findings are particularly relevant in floor gymnastics, where asymmetric landings and rapid changes of direction often occur after acrobatic movements. The prevalence of knee valgus mechanics underscores the need for biomechanical assessments that go beyond sagittal plane analysis.

The reviewed evidence emphasizes that landing is a neuromuscularly complex, multi-joint task requiring coordinated energy expenditure across the hip, knee, and ankle joints. Studies examining neuromuscular variables suggest that inadequate eccentric muscle control and delayed muscle activation patterns may impair joint stability during landing (Mekić et al., 2025). Specifically, reduced pre-activation or delayed activation of the quadriceps, hamstring, and ankle stabilizer muscles may limit the ability to control joint loading, thereby increasing susceptibility to injury (Williams et al., 2022). Despite these insights, many studies analyze biomechanical variables in isolation, focusing on single joints or discrete parameters. This reductionist approach presents a significant limitation, as it fails to capture the interactive nature of joint coordination during real-world landings. The lack of an integrated kinematic-kinetic-neuromuscular model limits the ability to fully explain injury mechanisms in floor gymnastics and highlights a significant gap in the current literature.

A key finding of this review is substantial methodological heterogeneity across studies. Variations in participant characteristics (age, gender, skill level), landing tasks (fall landings vs. skill-specific landings), and measurement technologies limit comparisons between studies. Furthermore, inconsistencies in outcome variables and data normalization methods hamper the synthesis of biomechanical evidence and the identification of robust injury risk thresholds. Another critical gap identified is the limited number of longitudinal and intervention-based studies. Most included studies used cross-sectional designs, which provide valuable descriptive information but limited insight into the causal relationship between landing biomechanics and injury occurrence. Consequently, the extent to which identified biomechanical risk factors predict future injury in floor gymnastics remains unclear. These limitations hamper the translation of biomechanical findings into evidence-based injury prevention programs.

Despite these limitations, the findings of this review have important implications for injury prevention. The consistent association between safer landing mechanics characterized by increased joint flexion, reduced vGRF, and controlled frontal plane movements and lower injury risk suggests that biomechanical assessment should be integrated into routine training and screening practices. Technique-focused interventions aimed at improving landing mechanics, combined with neuromuscular and strength training, may improve athletes' ability to safely absorb impact forces. Importantly, the lack of a standardized biomechanical assessment framework is a barrier to implementation.

Developing consensus on key biomechanical indicators and testing protocols will facilitate the translation of research findings into applied settings. Such a framework can support coaches, clinicians, and sport scientists in identifying high-risk movement patterns and monitoring the effectiveness of injury prevention interventions.

Future research should prioritize the development of standardized, multidimensional biomechanical assessment models that integrate kinematic, kinetic, and neuromuscular data. Longitudinal studies linking

Conclusion

This systematic review highlights the crucial role of biomechanical analysis in understanding injury mechanisms associated with landing movements in floor gymnastics. The synthesized evidence indicates that excessive vertical ground reaction forces, limited lower limb joint flexion, increased knee valgus, and inadequate neuromuscular control are consistently associated with increased injury risk. These biomechanical characteristics underscore the importance of coordinated multi-joint energy absorption strategies to reduce impact forces during landing. A key contribution of this review lies in identifying substantial methodological and conceptual gaps in the existing literature. Despite the increasing number of biomechanical studies in gymnastics, the existing evidence remains fragmented due to heterogeneity in study designs, measurement protocols, and outcome variables. Furthermore, the predominance of cross-sectional approaches and the limited integration of kinematic, kinetic, and neuromuscular data limit the translation of biomechanical findings into effective injury prevention strategies.

From an applied perspective, these findings emphasize the need for a standardized biomechanical assessment framework that can be applied across research and training environments. Integrating biomechanical-based screening and technique-focused interventions into floor gymnastics training can improve movement quality and reduce injury risk. Importantly, future research should prioritize longitudinal, intervention-based designs to establish causal relationships between landing biomechanics and injury outcomes and to evaluate the effectiveness of targeted prevention programs. In conclusion, advancing injury prevention in floor gymnastics requires a shift from isolated biomechanical observations to integrated, standardized, and application-oriented research. Such an approach will not only strengthen the scientific evidence base but also support the development of safer training practices for gymnasts at all performance levels.

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Conflict Of Interest
The author declares that there is no conflict of interest

Reference

Abouzeid, N., Gepfert, M., Alaqil, A. I., Bursais, A. K., Hashoos, H., Alibrahim, M. S., Moseekh, L. Z., & Hamza, A. S. (2026). Effects of bungee-based training on physical performance and arch jump kinematics in female college rhythmic gymnasts. *Baltic Journal of Health and Physical Activity*, *18*(1), 4.

Ahsan, M., & Alzahrani, A. (2024). The effect of the quadriceps muscle on sports performance and injury prevention: biomechanical perspective. *Tuijin Jishu/Journal of Propulsion Technology*, *45*(4), 2024.

Almeida, M. O., Davis, I. S., & Lopes, A. D. (2015). Biomechanical differences of foot-strike patterns during running: a systematic review with meta-analysis. *Journal of Orthopaedic \& Sports Physical Therapy*, *45*(10), 738–755.

Belkhelladi, M., Cierson, T., & Martineau, P. A. (2025). Biomechanical risk factors for increased anterior cruciate ligament loading and injury: a systematic review. *Orthopaedic Journal of Sports Medicine*, *13*(2), 23259671241312680.

Bocheng, C., Ziyan, Y., Jiaxin, W., Wang, G., & Tiancheng, Y. (2024). Effects of 16 weeks of plyometric training on knee biomechanics during the landing phase in athletes. *European Journal of Sport Science*, *24*(8), 1095–1109. https://doi.org/https://doi.org/10.1002/ejsc.12174

Bonazza, N. A., Saltzman, E. B., Wittstein, J. R., Richard, M. J., Kramer, W., & Riboh, J. C. (2022). Overuse Elbow Injuries in Youth Gymnasts. *The American Journal of Sports Medicine*, *50*(2), 576–585. https://doi.org/10.1177/03635465211000776

Chen, B., Wu, J., Jiang, J., & Wang, G. (2025). Neuromuscular and Biomechanical Adaptations of the Lower Limbs During the Pre-Landing and Landing Phase of Running Under Fatigue Conditions. *Applied Sciences*, *15*(5). https://doi.org/10.3390/app15052449

Chou, T.-Y., Huang, Y.-L., Leung, W., Brown, C. N., Kaminski, T. W., & Norcross, M. F. (2023). Does prior concussion lead to biomechanical alterations associated with lateral ankle sprain and anterior cruciate ligament injury? A systematic review and meta-analysis. *British Journal of Sports Medicine*, *57*(23), 1509–1515.

Hu, Z., Kim, Y., Zhang, Y., Zhang, Y., Li, J., Tang, X., Sohn, J., & Kim, S. (2022). Correlation of Lower Limb Muscle Activity with Knee Joint Kinematics and Kinetics during Badminton Landing Tasks. *International Journal of Environmental Research and Public Health*, *19*(24). https://doi.org/10.3390/ijerph192416587

Krause, A. T., Snodgrass, S. J., Edwards, S., McNally, T., & Osmotherly, P. G. (2023). Understanding the influences on horizontal jump landing mechanics: A systematic review. *International Journal of Sports Science \& Coaching*, *18*(5), 1867–1881.

Larwa, J., Stoy, C., Chafetz, R. S., Boniello, M., & Franklin, C. (2021). Stiff landings, core stability, and dynamic knee valgus: a systematic review on documented anterior cruciate ligament ruptures in male and female athletes. *International Journal of Environmental Research and Public Health*, *18*(7), 3826.

Li, D., Liu, Y., Feng, Y., Peng, C., & Tang, D. (2025). Interlimb asymmetries of lower limb isometric strength for predicting plantar fasciitis in male amateur marathon runners: a prospective cohort study. *BMC Sports Science, Medicine and Rehabilitation*, *17*(1), 255.

Li, L., Luo, Y., Wang, R., Huo, D., Song, B., Hao, Y., & Zhou, Y. (2025). Optical Fiber Sensing Technology for Sports Monitoring: A Comprehensive Review. *Photonics*, *12*(10), 963.

Malisoux, L., Gette, P., Backes, A., Delattre, N., & Theisen, D. (2023). Lower impact forces but greater burden for the musculoskeletal system in running shoes with greater cushioning stiffness. *European Journal of Sport Science*, *23*(2), 210–220.

Mekić, R., Milić, V., Radenković, O., Čaprić, I., Veličković, S., Mujanović, R., Biševac, E., Mahmutović, E., Salihagić, Z., Ajdinović, A., & others. (2025). Injuries in artistic gymnastics: Etiology, prevention Strategies, and multifactorial Perspectives—A systematic review. *International Journal of Molecular Sciences*, *26*(22), 10929.

Skopal, L., Netto, K., Aisbett, B., Takla, A., & Castricum, T. (2020). The effect of a rhythmic gymnastics-based power-flexibility program on the lower limb flexibility and power of contemporary dancers. *International Journal of Sports Physical Therapy*, *15*(3), 343.

Thomas, R. E., & Thomas, B. C. (2019). A systematic review of injuries in gymnastics. *Physician and Sportsmedicine*, *47*(1), 96–121. https://doi.org/10.1080/00913847.2018.1527646

Williams, E. R., Lloyd, R. S., Moeskops, S., & Pedley, J. S. (2022). Assessing and Monitoring Injury Risk Factors in Young Gymnasts. *Strength \& Conditioning Journal*, 10–1519.

Xu, D., Jiang, X., Cen, X., Baker, J. S., & Gu, Y. (2020). Single-leg landings following a volleyball spike may increase the risk of anterior cruciate ligament injury more than landing on both-legs. *Applied Sciences*, *11*(1), 130.

Zaki, B. Ben, Julia, M., Desmyttere, G., Perrey, S., & Dusfour, G. (2025). Altered landing strategy during vertical jump tasks in elite volleyball players with patellar tendinopathy. *Physical Therapy in Sport*, *74*, 96–103.

Zhou, Z., Harun, M. T., Peng, H., & Ye, W. (2025). Biomechanical research on ACL: A narrative bibliometric review. *Journal of Physical Education and Sport*, *25*(11), 2230–2248.

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