International Journal of Research in Orthopaedics
Uddin SM et al. Int J Res Orthop. 2026 Sep;12(5):1475-1483
https://www.ijoro.org

DOI: https://dx.doi.org/10.18203/issn.2455-4510.IntJResOrthop20262922

Systemic Review

The role of jumping and landing patterns in anterior cruciate ligament injury risk: a systematic review of assessment methods

Syed Maaz Uddin*, Andrew Murphy

University of Dundee, Dundee, Scotland, United Kingdom

Received: 30 April 2026
Accepted: 11 June 2026

***Correspondence:**
Dr. Syed Maaz Uddin,
E-mail: dr.maazuddinsyed@gmail.com

ABSTRACT

Anterior cruciate ligament (ACL) injuries are a major concern in orthopaedic and sports medicine, with non-contact mechanisms accounting for the majority of cases. Faulty jump-landing biomechanics, including altered joint kinematics and neuromuscular deficits, have been identified as key modifiable risk factors. This systematic review aimed to evaluate the role of jumping and landing patterns in ACL injury risk and to assess the effectiveness of biomechanical assessment tools and preventive interventions. A systematic review was conducted in accordance with PRISMA guidelines. Electronic databases, including PubMed, ScienceDirect, and ClinicalTrials.gov, were searched up to October 2024. Studies involving adults (≥18 years) that assessed jump-landing biomechanics using validated tools such as three-dimensional motion analysis, electromyography, and force plates were included. A total of 120 studies were identified, of which 15 met the inclusion criteria. Data extraction and quality assessment were performed using a structured framework and the Critical appraisal skills programme checklist. Fifteen studies were included, encompassing various study designs and populations. The most consistent biomechanical risk factors identified were increased knee valgus, reduced knee flexion, and poor trunk stability during landing. Fatigue was found to exacerbate these deficits, leading to compromised neuromuscular control. Assessment tools such as motion analysis, electromyography, and force plates effectively identified these risk patterns. Preventive interventions, particularly neuromuscular and plyometric training, demonstrated significant improvements in landing mechanics and reduction in injury risk. Jump-landing biomechanics play a critical role in ACL injury risk. Identification of modifiable risk factors through validated assessment tools allows targeted preventive strategies. Neuromuscular training programs are effective in improving biomechanics and reducing injury incidence; however, broader clinical implementation and long-term adherence remain challenges.

Keywords: Anterior cruciate ligament, Jump-landing biomechanics, Knee valgus, Neuromuscular training, Injury prevention, Force plate analysis

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are among the most prevalent and debilitating musculoskeletal injuries encountered in athletes and physically active individuals, particularly those engaged in high-impact sports such as football, basketball, volleyball, and skiing. With an estimated annual incidence of 68.6 per 100,000 person-years, ACL injuries represent a substantial public health burden due to their significant economic impact and long-term consequences on joint health and functional outcomes.[1,2] The ACL functions as a primary stabilizer of the knee joint by restricting anterior tibial translation and controlling rotational loads, particularly during dynamic activities such as jumping, landing, and pivoting.[3,4] ACL injuries are broadly classified into contact and non-contact mechanisms. Contact injuries result from direct external forces applied to the knee, whereas non-contact injuries occur in the absence of such forces and are typically associated with intrinsic biomechanical and neuromuscular factors. Notably, non-contact mechanisms account for approximately 70-75% of all ACL injuries and are frequently linked to aberrant movement patterns during landing tasks.[5-7]

Several biomechanical factors have been consistently implicated in increasing the risk of non-contact ACL injuries. One of the most prominent risk factors is an increased knee valgus angle during landing, characterised by excessive medial collapse of the knee joint, which imposes abnormal stress on the ACL. This phenomenon is particularly pronounced in female athletes, who demonstrate a higher tendency for valgus collapse compared to males.[8-10] In addition, reduced knee flexion during landing has been shown to impair the dissipation of ground reaction forces, thereby increasing anterior tibial shear forces and placing the ACL under greater strain.[11,12] Furthermore, poor trunk stability contributes significantly to injury risk by altering the body's centre of mass, resulting in compensatory lower limb mechanics that further increase knee valgus loading and ligament stress.[13,14]

Fatigue has emerged as a critical modifier of these biomechanical deficits. As fatigue develops, neuromuscular control deteriorates, leading to an increased reliance on quadriceps-dominant activation patterns and reduced hamstring co-activation. This imbalance compromises the dynamic stabilisation of the knee joint and further elevates the risk of ACL injury during high-intensity activities.[15,16]

The implications of ACL injuries extend well beyond the initial trauma. Long-term sequelae include a significantly increased risk of post-traumatic osteoarthritis (PTOA), which has been reported to develop in up to 50% of individuals within 10-20 years following injury, irrespective of surgical reconstruction.[17,18] Additionally, the physical limitations and psychological burden associated with prolonged rehabilitation often impact an individual's quality of life and may compromise athletic performance and career longevity.[19,20]

Advancements in biomechanical assessment techniques have facilitated a more precise understanding of modifiable risk factors associated with ACL injuries. Technologies such as three-dimensional motion analysis, electromyography (EMG), and force plate systems allow for objective quantification of joint kinematics, muscle activation patterns, and ground reaction forces during dynamic tasks.[21-23] Motion capture systems provide detailed insights into movement patterns and joint loading, while EMG enables the evaluation of neuromuscular imbalances between agonist and antagonist muscle groups.[24,25] These tools have played a pivotal role in the development of targeted preventive interventions, including neuromuscular training and plyometric exercise programs, which have demonstrated substantial reductions in ACL injury risk, ranging from 50% to 70%.[26,27]

Despite these advancements, the translation of biomechanical assessment techniques and preventive strategies into routine clinical and sports practice remains inconsistent. Variability in accessibility, implementation, and standardisation of assessment protocols continues to limit their widespread adoption. Therefore, this systematic review aims to synthesise current evidence on jump-landing biomechanics, critically evaluate the tools used for assessing ACL injury risk, and highlight evidence-based interventions that can be effectively integrated into clinical and athletic settings to reduce injury prevalence.

METHODS

Study design

This systematic review was conducted following the PRISMA (preferred reporting items for systematic reviews and meta-analyses) guidelines to ensure transparency and methodological rigor.[26] The PRISMA framework facilitates a standardized approach to study selection, data extraction, and reporting, making it suitable for systematic reviews focused on assessing risk factors and intervention efficacy.[27]

The review aimed to synthesize evidence on jump-landing biomechanics as risk factors for ACL injuries and to evaluate the tools used to measure these deficits, such as 3D motion analysis, electromyography (EMG), and force plates. This design allowed for the inclusion of diverse study designs, including randomized controlled trials (RCTs), cohort studies, and case-control studies.

This systematic review was not prospectively registered in the PROSPERO database. The study was conducted as part of an MSc research project, and at the time of initiation, protocol registration was not mandated. However, all methodological steps were predefined and strictly adhered to established PRISMA guidelines to ensure transparency, reproducibility, and methodological rigor.

Search strategy

A comprehensive and systematic literature search was performed across multiple electronic databases, including PubMed, ScienceDirect, and ClinicalTrials.gov. The search strategy was developed based on a combination of Medical subject headings (MeSH) and free-text terms relevant to ACL injury mechanisms and biomechanical assessment.

Search terms included combinations of keywords such as "anterior cruciate ligament injury," "jump-landing biomechanics," "knee valgus," "knee flexion," "landing mechanics," "motion analysis," "force plates," and "electromyography." Boolean operators (AND, OR) were used to refine the search and ensure comprehensive retrieval of relevant studies. The search was restricted to studies published in the English language and involving human participants aged 18 years and above. Studies published up to October 2024 were included to ensure that the most recent and clinically relevant evidence was captured.[28] Additionally, the reference lists of included articles were manually screened to identify any studies that may not have been retrieved through database searches.[29]

Inclusion and exclusion criteria

Studies were considered eligible for inclusion if they evaluated jump-landing biomechanics or neuromuscular-related factors as potential risk contributors to ACL injury. Only studies involving adult populations (≥18 years) were included to ensure homogeneity in biomechanical and physiological characteristics.

Eligible studies were required to utilise validated biomechanical assessment tools such as three-dimensional motion analysis systems, Electromyography (EMG), or force plates. Furthermore, studies had to report outcomes related to key biomechanical variables including knee valgus, knee flexion, trunk stability, or muscle activation patterns during dynamic tasks such as jumping or landing.

Studies were excluded if they focused primarily on post-operative outcomes following ACL reconstruction, involved paediatric populations, or were not available in full text. Non-English publications were also excluded due to feasibility constraints.

Study selection

The initial search yielded a total of 120 studies. Following the removal of duplicate records, 95 unique studies remained for screening. Titles and abstracts were reviewed to assess relevance, resulting in 45 studies being selected for full-text evaluation.

After applying the predefined eligibility criteria, 15 studies were included in the final analysis. The study selection process was conducted systematically and is illustrated in the PRISMA flow diagram (Figure 1), detailing the stages of identification, screening, eligibility, and inclusion.

Data extraction

Data extraction was performed systematically from all included studies using a predefined framework. Extracted data included study characteristics such as author details, study design, sample size, participant demographics, type of biomechanical risk factor assessed, and the assessment methods employed.

Additional information regarding outcome measures, including kinematic variables, muscle activation patterns, and ground reaction forces, was also extracted. This structured approach ensured consistency and accuracy in synthesising findings across studies.

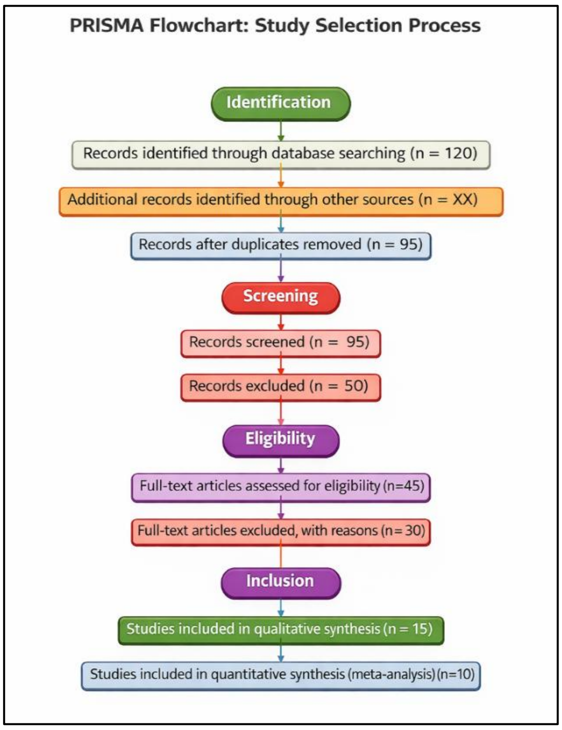

Figure 1: PRISMA flowchart summarizing the stages of study selection, identification, screening, eligibility and inclusion.

Quality assessment

The methodological quality of the included studies was assessed using the CASP checklist, which is designed to evaluate both randomized and observational study designs. The CASP tool systematically assesses study validity, methodological rigor, clarity of results, and applicability to clinical practice.[30] In addition to overall quality assessment, the CASP framework inherently incorporates evaluation of potential sources of bias, including selection bias, performance bias, detection bias, and confounding. Each study was critically appraised with particular emphasis on study design, participant selection, outcome measurement, and consistency of reporting. The appraisal process was conducted independently, and discrepancies were resolved through discussion to ensure consistency in evaluation. All included studies demonstrated acceptable methodological quality and were deemed suitable for inclusion in the final synthesis.[31]

Data synthesis

A qualitative synthesis of the included studies was performed due to the heterogeneity in study designs, participant characteristics, outcome measures, and biomechanical assessment methods. The included studies employed diverse methodologies, including three-dimensional motion analysis, electromyography, force plate assessments, and varied fatigue protocols, which precluded direct quantitative comparison. Given this methodological variability, a meta-analysis was not performed, as pooling of data would not yield clinically meaningful or statistically valid conclusions. Instead, findings were synthesised narratively, focusing on the identification of consistent biomechanical risk factors, assessment tools, and preventive strategies across studies. This approach ensured that the synthesis remained clinically relevant while the preserving the integrity and interpretability of the individual study findings.

RESULTS

This systematic review analysed findings from 15 studies that investigated jump-landing biomechanics as risk factors for ACL injuries. These studies employed a range of methodologies, including 3D motion analysis, EMG, and force plates, to identify biomechanical deficits associated with ACL injuries.

Table 1: Summary of included studies.

Author	Study design	Risk factor	Methodology	Key findings
Hewettet al, (2005)[6]	Cohort	Knee valgus	3D motion analysis	Knee valgus predicts ACL injury risk.
Sellet al, (2007)[31]	Case-controlled	Knee flexion deficit	EMG, force plates	Reduced flexion increases ACL strain.
Kernozeket al, (2008)[10]	Cohort	Fatigue	3D motion analysis	Fatigue increases knee valgus strain.
Zazulaket al, (2007)[13]	Cohort	Trunk instability	Core strength testing	Poor trunk control raises ACL risk.
Olsenet al, (2004)[12]	RCT	Landing asymmetry	Video analysis, force plates	Asymmetry correlates with ACL injury.
Eliaset al, (2016)[32]	RCT	Co-contraction deficit	EMG, plyometric testing	Training improved neuromuscular control.
Yuet al, (2007)[11]	Case-controlled	Valgus collapse	Motion analysis	Valgus collapse stresses ACL fibres.
Myeret al, (2008)[33]	Cohort	Neuromuscular deficits	Plyometric assessment	Training reduced ACL injury incidence.
Benjaminseet al, (2011)[19]	RCT	Fatigue	Fatigue protocol+EMG	Fatigue worsens biomechanics.
Zebiset al, (2016)[14]	Cross-sectional	Quadriceps dominance	EMG	Quadriceps dominance stresses ACL.
Jeonget al,[34]	RCT	Core stability	Trunk stability exercises	Improved core stability reduced valgus.
Swärdet al, (2010)[35]	Cohort	Tibial slope	Imaging, biomechanics	Increased tibial slope raises ACL risk.
Cochraneet al, (2007)[36]	Case-controlled	Foot positioning	3D motion capture	Foot misalignment increases ACL risk.
Nylandet al, (2014)[15]	Cohort	Compensatory patterns	Force plates, EMG	ACL injuries alter muscle patterns.
Markatoset al, (2013)[21]	Cross-sectional	ACL anatomical variance	Imaging	ACL anatomy influences injury risk.

Table 2: Key biomechanical variables and assessment tools.

Biomechanical variables	Assessment tool	Relevance to ACL injury risk
Knee valgus angle	3D motion analysis, video analysis	Excessive valgus increases ACL strain, particularly in female athletes
Knee flexion angle	3D motion analysis, electrogoniometer	Reduced flexion leads to higher anterior tibial shear forces
Trunk stability	Core strength testing, trunk stability index	Poor trunk stability shifts centre of mass, increasing knee valgus
Ground reaction force	Force plates, pressure sensors	Higher ground reaction forces contribute to ACL loading

Continued.

Biomechanical variables	Assessment tool	Relevance to ACL injury risk
Muscle activation patterns	Electromyography (EMG), surface EMG sensors	Imbalanced muscle activation leads to improper landing mechanics.

Table 3: Comparison of landing techniques.

Landing techniques	Biomechanical characteristics	Risk of ACL injury
Soft landing	Increased knee flexion, reduced ground reaction force	Lower risk due to better force absorption
Stiff landing	Minimal knee flexion, high ground reaction force	Higher risk due to increased anterior tibial shear forces
Asymmetric landing	Unequal weight distribution, increased knee valgus	Higher risk due to uneven loading and knee instability
Forefoot landing	Higher forefoot pressure, potential calf strain	Moderate risk: potential ankle instability affects knee alignment
Heel-strike landing	Higher impact forces, increased tibial shock	Higher risk due to excessive ground impact and poor shock absorption

Table 4: Fatigue impact on jump landing.

Fatigue conditions	Observed biomechanical changes	Impact on ACL injury risk
General fatigue	Increased knee valgus, reduced knee flexion	Higher risk due to compromised neuromuscular control
Lower limb muscle fatigue	Quadriceps dominance, decreased hamstring activation	Increased ACL loading due to imbalance in muscle activation
Core muscle fatigue	Poor trunk control, increased postural sway	Higher knee instability, increased valgus angles
Cognitive fatigue	Slower reaction time, impaired landing coordination	Delayed protective reflexes, greater risk of improper landing
Repeated jumping fatigue	Progressive reduction in jump height, altered force absorption	Increased joint stress, cumulative strain on ACL

Table 5: Preventive strategies for landing mechanics.

Preventive strategy	Key components	Impact on landing mechanics
Neuromuscular training	Dynamic warm-ups, agility drills, proprioceptive exercises	Enhances muscle coordination, reduces knee valgus
Plyometric exercises	Jump training, explosive movements, landing technique improvement	Improves shock absorption, increases knee flexion
Balance and proprioception training	Single-leg stance, unstable surface training, coordination drills	Enhances joint position awareness, reduces landing asymmetry
Core stability training	Plank variations, trunk control exercises, rotational stability drills	Improves trunk control, minimizes knee valgus and instability
Strength training	Quadriceps and hamstring strengthening, eccentric exercises	Enhances lower limb strength, stabilizes knee joint during impact

Characteristics of included studies

The characteristics of the 15 included studies are summarized in Table 1.

These studies varied in design (randomized controlled trials, cohort studies, and case-control studies), populations (athletes and physically active individuals), and methodologies for assessing jump-landing biomechanics (Table 2).

Biomechanical risk factors identified

The included studies identified three primary biomechanical deficits contributing to ACL injury risk (Table 3).

Increased knee valgus angle

Increased knee valgus is the most frequently cited risk factor for ACL injuries. Multiple studies using 3D motion analysis demonstrated a strong correlation between valgus collapse during landing and ACL loading, particularly in female athletes who are more prone to valgus movements due to anatomical and hormonal differences.[6,11,32]

Reduced knee flexion

Landing with reduced knee flexion increases anterior tibial shear forces, significantly elevating ACL strain. Studies employing motion analysis and force plates found that athletes with stiff landings and decreased knee flexion were at higher risk for ACL injuries.[32,34]

Poor trunk stability

Trunk instability, characterized by excessive lateral or anterior movement of the torso during landing, was another critical risk factor. Studies found that poor core control shifts the center of mass, exacerbating knee valgus and increasing ACL strain.[13,35]

Influence of fatigue on landing mechanics

Fatigue was identified as a significant modifier of jump-landing biomechanics. Key findings across studies include (Table 4).

Increased knee valgus

Fatigue exacerbated valgus collapse, further increasing ACL loading.[10,20]

Reduced knee flexion

Athletes exhibited stiffer landings with less knee flexion under fatigued conditions.[32,34]

Compromised neuromuscular activation

EMG analysis revealed reduced hamstring co-activation and increased quadriceps dominance, both of which are detrimental to ACL stability.[14,20]

Preventive interventions

Preventive interventions were evaluated in multiple studies, with significant improvements observed in landing mechanics and ACL injury rates. Common strategies included (Table 4).

Neuromuscular training

Programs combining plyometric exercises, balance training, and core strengthening demonstrated substantial reductions in knee valgus angles and improvements in landing mechanics.[33-35]

Plyometric training

Plyometric exercises were particularly effective in increasing knee flexion during landing, reducing ground reaction forces and ACL strain.[34]

Core stability exercises

Trunk stability training improved core control, minimizing anterior center-of-mass shifts and knee valgus during dynamic movements.[13,35]

Summary of findings

The findings from this review highlight three critical risk factors knee valgus, reduced knee flexion, and poor trunk stability as key contributors to ACL injury risk. Tools such as 3D motion analysis, EMG and force plates were instrumental in identifying these deficits and informing preventive strategies.

DISCUSSION

The findings of this systematic review highlight the central role of biomechanical deficits in the pathogenesis of ACL injuries and reinforce the importance of evaluating jump-landing mechanics as a means of identifying individuals at increased risk. By synthesising evidence from multiple studies, this review provides a comprehensive understanding of key modifiable risk factors and their implications for injury prevention and clinical practice.

A consistent observation across the included studies was the strong association between increased knee valgus and ACL injury risk. Knee valgus, characterised by medial collapse of the knee during dynamic activities, imposes excessive strain on the ACL and significantly increases ligament loading. This biomechanical pattern is particularly prevalent among female athletes, who exhibit a higher predisposition to valgus collapse due to a combination of anatomical, hormonal, and neuromuscular factors.[6,11,32] Evidence derived from three-dimensional motion analysis further supports this relationship, demonstrating that athletes with greater valgus angles during jump-landing tasks are more susceptible to ACL injury.[6,10] These findings underscore the importance of incorporating valgus angle assessment into routine biomechanical screening protocols for early risk identification.

Reduced knee flexion during landing emerged as another critical determinant of ACL injury risk. Inadequate knee flexion limits the ability of the lower limb to dissipate ground reaction forces effectively, thereby increasing anterior tibial translation and placing the ACL under greater mechanical stress. Athletes exhibiting “stiff” landing patterns, characterised by minimal knee flexion, are less able to engage protective neuromuscular mechanisms such as hamstring co-contraction, further exacerbating injury risk.[32,34] These observations are consistent with previous literature and suggest that interventions aimed at promoting adequate knee flexion during landing may play a significant role in reducing ACL injury incidence.[20]

Trunk stability also emerged as a key modifiable factor influencing ACL injury risk. Poor control of the trunk alters the body's centre of mass and contributes to compensatory lower limb mechanics, including increased knee valgus and abnormal loading patterns. The studies included in this review demonstrated a clear association between inadequate core stability and biomechanical deficits during landing tasks.[8,35] These findings align with existing evidence identifying trunk control as a critical component of neuromuscular stability, particularly in sports requiring rapid directional changes and high-impact movements.[23,35] Strengthening of core musculature and enhancement of trunk control may therefore represent an essential component of ACL injury prevention strategies.

Fatigue was identified as a significant modifier of biomechanical risk factors, with multiple studies demonstrating its detrimental effects on neuromuscular control. Fatigue leads to altered movement patterns, including increased knee valgus, reduced knee flexion, and disrupted muscle activation sequences.[10,20,23] In particular, fatigue-induced reductions in hamstring activation and increased reliance on quadriceps-dominant strategies contribute to greater anterior tibial translation and elevated ACL strain.[20] These findings support the concept that fatigue not only exacerbates existing biomechanical deficits but may also introduce new risk factors, thereby increasing overall injury susceptibility.[23] Accordingly, the incorporation of fatigue-resistant training protocols and monitoring of fatigue levels during athletic performance are critical considerations in injury prevention.

Preventive interventions targeting jump-landing biomechanics were consistently shown to be effective in reducing ACL injury risk. Neuromuscular training programs incorporating plyometric exercises, balance training, and core stability exercises demonstrated significant improvements in landing mechanics and reductions in injury incidence.[33-35] Plyometric training, in particular, was associated with increased knee flexion and reduced valgus collapse during landing, reinforcing its role as a cornerstone of ACL injury prevention.[34] Similarly, core stability interventions improved trunk control and reduced compensatory movement patterns, highlighting the importance of comprehensive, multi-component training programs in addressing biomechanical deficits.[35]

Despite these important findings, several limitations must be acknowledged. The heterogeneity of study designs, participant characteristics, and assessment methodologies may limit the generalisability of the results. Variations in factors such as age, sex, and athletic experience across studies may influence the applicability of findings to specific populations.[20,32] Furthermore, the majority of studies utilised laboratory-based biomechanical assessments, which may not fully replicate the dynamic and unpredictable conditions encountered in real-world sporting environments.[10,33] Future research should prioritise field-based assessments to better capture sport-specific movement patterns and enhance ecological validity.

Another notable limitation is the lack of standardisation in fatigue assessment protocols. While fatigue was widely recognised as a contributing factor to ACL injury risk, the variability in methods used to induce and measure fatigue complicates comparisons across studies.[20,23] Establishing standardised fatigue protocols would improve the consistency and interpretability of future research. Additionally, although preventive interventions were shown to be effective, the long-term sustainability and adherence to these programs remain uncertain. Further research is required to evaluate the durability of training effects and to develop strategies that promote sustained engagement among athletes.

CONCLUSION

In conclusion, this systematic review reinforces the pivotal role of jump-landing biomechanics in ACL injury risk and highlights the value of advanced assessment tools such as three-dimensional motion analysis, electromyography, and force plates in identifying at-risk individuals. Addressing modifiable biomechanical deficits, including increased knee valgus, reduced knee flexion, and poor trunk stability, through targeted intervention strategies is essential for reducing the incidence of ACL injuries. Future research focusing on standardisation of assessment methods and the integration of field-based evaluations will further enhance the development of effective and clinically applicable prevention strategies.

ACKNOWLEDGEMENTS

The author would like to express sincere gratitude to the supervisor/guide for his invaluable guidance, academic mentorship, and continuous support throughout the course of this research. The author also acknowledges the university for providing the academic environment and resources necessary for the successful completion of this study as part of the MSc in orthopaedic sciences.

Funding: No funding sources
Conflict of interest: None declared
Ethical approval: Not required

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Cite this article as: Uddin SM, Murphy A. The role of jumping and landing patterns in anterior cruciate ligament injury risk: a systematic review of assessment methods. Int J Res Orthop 2026;12:1475-83.