Biomechanical Risk Factors for Increased Anterior Cruciate Ligament Loading and Injury

A Systematic Review

Malachy Belkhelladi,*† BA, Tanya Cierson,† BS, and Paul A. Martineau,† MD
Investigation performed at McGill University Health Centre, Montreal, Quebec, Canada

Background: Understanding the biomechanical risk factors for noncontact anterior cruciate ligament (ACL) injury can inform machine learning models, aid in prevention strategies, and guide rehabilitation protocols, reducing the incidence and burden of these injuries in both athletes and the general population.

Purpose: To determine the biomechanical risk factors associated with noncontact ACL injury and increased knee loading.

Study Design: Systematic review; Level of evidence, 4.

Methods: A literature search was conducted according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Randomized, cohort, case-control, and cross-sectional studies identifying noncontact biomechanical risk factors for ACL injuries published before May 2023 were included in this review. Excluded were studies focused on contact ACL injuries, those focused on biomechanical risk factors postinjury, and those not published in the English language. The authors highlighted biomechanical risk factors not extensively covered in previous reviews, including the toe-in position, increased contralateral pelvic hike, increased hip internal rotation angle, and specific ankle angles. A quantitative overview of the included studies was conducted, highlighting the frequency of each biomechanical factor reported as potentially related to ACL injury or loading risk.

Results: A total of 28 studies (2819 athletes) were selected for analysis. The majority of these studies (22/28) were cross-sectional, primarily assessing ACL load indirectly via knee valgus moment or ground-reaction forces, while case-control and cohort studies focused on ACL injury incidence. Overall, 83% (5/6) of the studies assessing upper body biomechanics found that trunk flexion/extension and perturbations affect ACL loading risk. Of studies assessing hip biomechanics, 83% (10/12) showed increased ACL loading or injury risk with increased hip abduction/internal rotation angles. For the foot and ankle, increased toe-in/toe-out landing in 67% of studies (2/3) demonstrated higher stress on the ACL. Knee biomechanics were associated with increased ACL loading in 100% of the respective studies (5/5), with decreased knee flexion angles leading to increased loading.

Conclusion: The data demonstrated that factors associated with increased medial knee alignment, sagittal alignment of the trunk, and decreased lateral trunk flexion reduced both knee loading and ACL injury risk. Targeted prevention and detection strategies addressing high-risk biomechanics may reduce injury incidence, underscoring the need for further research to optimize intervention programs.

Keywords: ACL; biomechanics; knee joint kinematics; risk factors; noncontact injury; injury prevention

The anterior cruciate ligament (ACL) is a critical stabilizing structure in the knee. Its main anatomic purpose is to control anterior translation of the tibia from the femur and limit tibial rotation. It is particularly important for athletes involved in cutting, pivoting, or jumping sports.[40] The mechanisms of ACL injury are broadly categorized into contact and noncontact injuries. Contact ACL injuries are due to a direct impact on the knee, often seen in sports like football or rugby where physical collisions are common.[3] On the other hand, noncontact ACL

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injuries occur in the absence of direct external force, often during abrupt changes in direction, landing from a jump unstably, or sudden deceleration, common in sports like soccer and basketball.[3] The distinction between these 2 mechanisms is pivotal as it influences the preventive measures that can be adopted to mitigate the risk of ACL injuries.

ACL tears are multifactorial in nature, with biomechanical risk factors playing a pivotal role in noncontact ACL injuries. Suboptimal body mechanics, such as incorrect body positioning during landing or cutting maneuvers, can lead to increased knee loading and a higher risk of injury.[3] Recognition of these modifiable risk factors has led to the development of targeted interventions and training programs.[36] These programs often incorporate strength, neuromuscular, and plyometric exercises to improve muscle strength, proprioception, and movement mechanics.[36] Additionally, identifying risk factors can aid in developing predictive video analysis tools, which allow for early screening and prevention of ACL injuries.[26]

While numerous systematic reviews have explored these biomechanical risk factors, ongoing research continually provides new insights. Factors such as knee valgus moment, trunk position, and knee flexion angle were well established in a previous review by Hughes.[19] However, since the last systematic review on this topic, our analysis has identified numerous recent studies. These studies have presented several novel biomechanical risk factors, underscoring the need for an updated review of the literature. Therefore, in this systematic review we aimed to provide a comprehensive summary of the known biomechanical risk factors for ACL tears, critically evaluating the methodology and findings of these studies and building on knowledge established in previous reviews. Our secondary objective was to elucidate potential areas for future research that could further refine our understanding of these risk factors and lead to the development of more effective injury prevention strategies.

METHODS

Search Strategy

The Web of Science and PubMed databases were searched for articles published in print or electronically before May 2023. Additional records were identified through Google Scholar. The search strategy included the following terms: ("Anterior Cruciate Ligament" OR "ACL") NOT ("Reconstruction" OR "Surgery") AND "Injury" AND ("Trunk position" OR "Lower extremity alignment" OR "Hip position" OR "Knee position" OR "Landing biomechanics" OR "Cutting maneuvers" OR "Foot position" OR "Ground contact" OR "Arm position" OR "Biomechanics" OR "Risk Factors").

Selection Criteria

Studies were considered for inclusion if they (1) examined noncontact biomechanical risk factors for ACL injuries; (2) included any sex and age; (3) used one of the following study designs—randomized controlled trials, cohort studies, case-control studies, or cross-sectional studies; and (4) used reliable and valid methods to assess biomechanical risk factors and ACL injuries. (5) Only full-text, peer-reviewed studies published in the English language were included.

Exclusion criteria were as follows: (1) studies with non–English-language text; (2) those focusing on treatment or surgical intervention of ACL injuries rather than risk factors; (3) studies focusing on nonbiomechanical risk factors for ACL injuries (eg, genetic, anatomic, and hormonal factors); (4) studies including participants with a history of ACL injury; and (5) studies that did not provide original data, such as reviews, editorials, or opinion pieces, as well as studies focusing on animals or cadaveric models were excluded. (6) Studies were also excluded when the full text was not available.

The initial database searches identified 2511 articles for screening after removal of duplicates. After 2358 articles were excluded, 153 articles were selected for detailed review and were assessed for eligibility. After detailed review, 125 articles were excluded and 28 were included in the final review, encompassing a total of 2819 athletes. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[31] flow diagram of the search results is shown in Figure 1.

Data Extraction

Once articles meeting the inclusion criteria were identified, 2 reviewers (M.B. and T.C.) independently extracted information from each article. First, the titles and abstracts of each article were screened for relevance. Then, full articles were reviewed, and data were extracted if eligible. The main data points extracted from each article were the study design, study population, variables associated with ACL injury, and variables not associated with ACL injury. The screening tool Rayyan[30] was used to organize and screen studies.

Risk of Bias Assessment

Using the 14- and 12-item checklists for quality assessment of observational and cross-sectional studies and

*Address correspondence to Malachy Belkhelladi, BA, Division of Orthopaedic Surgery, McGill University Health Centre, 845 Sherbrooke Street West, Montreal, QC H3A 0G4, Canada (email: malachy.belkhelladi@mail.mcgill.ca).

†Division of Orthopaedic Surgery, McGill University Health Centre, Montreal, Quebec, Canada.

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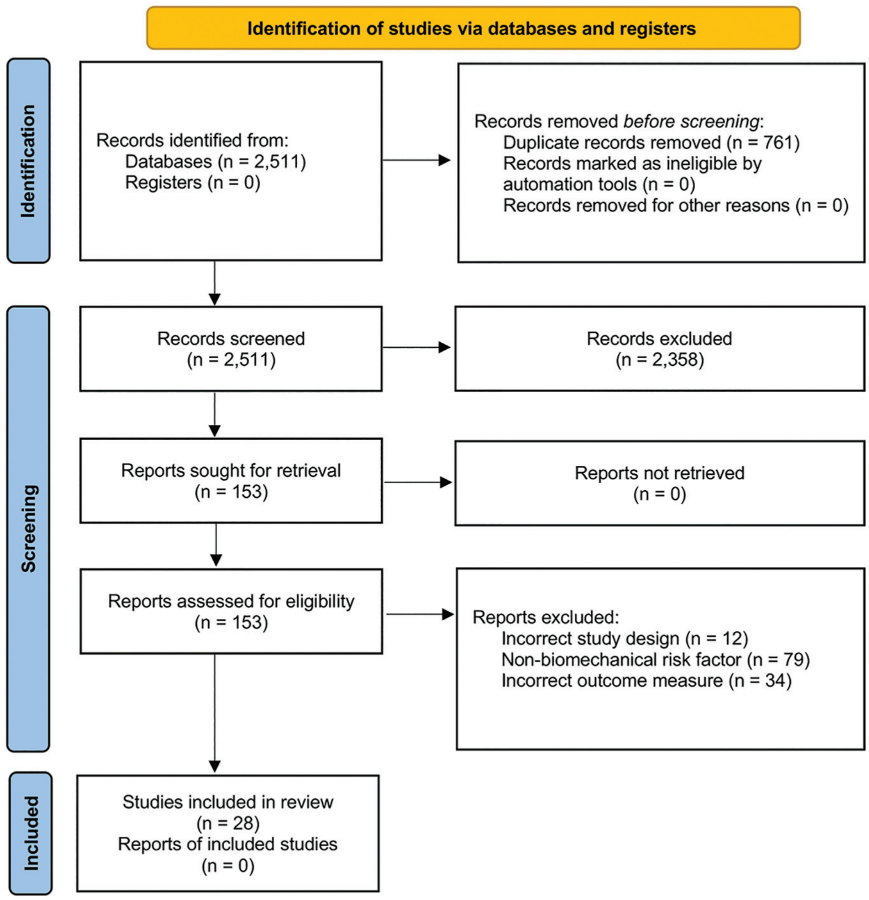

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)[31] flow diagram of search results.

quality assessment of case-control studies designed by the National Heart, Lung, and Blood Institute,[25] 2 reviewers (M.B. and T.C.) independently assessed the risk of bias for each study. These items assess study characteristics related to selection bias, attrition bias, and researcher bias. Studies were rated either poor, fair, or good by the lead author (M.B.) depending on their methodological quality.

Data Analysis

Descriptive statistics are used to summarize findings across the included studies. Each biomechanical factor was categorized as either associated or not associated with ACL injury or loading risk. The results are reported as percentages alongside the corresponding number of studies supporting each category. Given the heterogeneity in study designs, outcome measures, and populations, conducting a formal meta-analysis or statistical pooling was not feasible. No tests of statistical significance were performed. Instead, a frequency-based visualization was used to provide a quantitative overview of the literature, highlighting biomechanical factors consistently reported as potentially related to ACL injury or loading risk.

RESULTS

Characteristics of the Included Studies

Of the 28 included articles, 22 were cross-sectional studies,[‡] 5 were prospective cohort designs,[7,11,24,29,35] and 1 was a case-control design.[44] The risk of bias was rated as fair in 23 studies and as good in 5 studies. Thirteen of the 28 studies did not include both male and female participants. The mean age of participants ranged from 13.5 to 28.1 years, and patients from all but 1 study[38] were current athletes. The sample sizes ranged from 10 to 168 in the cross-sectional trials and 51 to 880 participants in the prospective cohort designs, whereas the case-control study had 173 participants. All 22 cross-sectional studies defined measure of ACL loading indirectly via increased knee valgus moment and/or increased ground-reaction forces; the characteristics of these studies are summarized in Table 1. The case-control study and the prospective cohort studies used ACL injury incidence as a measure for injury risk and are summarized in Table 2.

In all reviewed studies that measured ground-reaction forces,[§] force plates were used as the standard tool for

‡References 6, 8-10, 13-15, 18, 20, 23, 27, 33, 37-39, 41-43, 45-48.
§References 6, 8-10, 13-15, 18, 20, 23, 27, 33, 37, 39, 41-43, 45-48.

TABLE 1
Characteristics of Studies on ACL Loading (n = 22)[a]

Lead Author (Year)	Quality Rating[b]	Sample Size	Mean Age, y	Variables Associated With ACL Injury	Variables Not Associated With ACL Injury	Summary of Findings
Chi-Yin (2013)[6]	Fair	10 (5 M/5 F)	23.4	None	Arm position	None of the tested arm positions had a significant effect on knee loading.
Cortes (2012)[8]	Fair	20 (0 M/20 F)	20	Forefoot landing	NR	Forefoot landing increased knee loading, increasing ACL strain.
Cronin (2016)[9]	Fair	40 (0 M/40 F)	21	Hip extension	Hip abduction	Increased hip extension was related to lower knee loading.
Davis (2019)[10]	Fair	41 (18 M/23 F)	21.4	Trunk extension	NR	Midflight trunk extension resulted in increased knee loading.
Favre (2016)[13]	Fair	39 (21 M/18 F)	26.8	Knee flexion	NR	Increased knee flexion during landing led to decreased ACL loading.
Fong (2011)[14]	Fair	35 (17 M/18 F)	20.5	Ankle dorsiflexion ROM	NR	Decreased ankle dorsiflexion ROM was associated with increased ACL loading.
Frank (2013)[15]	Fair	30 (15 M/1 F)	20.7	Trunk flexion, hip internal rotation moment	NR	Increases in trunk flexion and hip internal rotation moment were associated with increased knee loading.
Hinshaw (2019)[18]	Fair	41 (18 M/23 F)	22	Trunk lateral flexion	NR	Midflight lateral trunk resulted in a landing pattern associated with increased ACL loading for the ipsilateral leg.
Ishida (2015)[20]	Fair	14 (0 M/14 F)	21	Toe-in landing, toe-out landing	NR	Both toe-in and toe-out landing positions were associated with increased knee loading.
Lee (2021)[23]	Fair	26 (26 M/0 F)	24.3	Ankle plantarflexion angle	NR	Increased plantarflexion angle was associated with decreased knee loading.
McLean (2005)[27]	Fair	20 (10 M/10 F)	20.7	Hip flexion, hip internal rotation, knee valgus angle	NR	Increased hip flexion, internal rotation, and initial knee valgus angle increased knee loading.
Pollard (2010)[33]	Fair	58 (0 M/58 F)	13.5	Knee flexion, hip flexion	NR	Decreased hip and knee flexion were associated with increased knee loading.
Saito (2022)[37]	Fair	40 (20 M/20 F)	20.2	Trunk extension, trunk lateral flexion, trunk flexion	NR	Increased trunk extension and lateral flexion increased ACL loading.
Sakurai (2020)[38]	Fair	27 (27 M/0 F)	NR	Toe-in landing	Toe-out, toe-neutral landings	ACL loading in toe-in landing was larger than in toe-neutral and toe-out conditions.
Shimokochi (2013)[39]	Fair	20 (10 M/10 F)	23.4	Trunk flexion, trunk extension	NR	Increased trunk flexion was associated with decreased knee loading.
Sigurðsson (2021)[41]	Fair	168 (57 M/111 F)	NR	Knee flexion angle, foot-trunk distance, knee flexion excursion	NR	Decreased knee flexion angle, increased flexion excursion, and foot-trunk distance increased knee loading forces.
Sigward (2015)[42]	Fair	45 (25 M/20 F)	18.5	Hip internal rotation angle, hip abduction angle	NR	Increased hip abduction angle and decreases in hip internal rotation angle were associated with increased knee loading.
Song (2023)[43]	Fair	32 (16 M/16 F)	21.6	Upper trunk perturbation	NR	Upper trunk perturbation increased ACL loading.

(continued)

TABLE 1
(continued)

Lead Author (Year)	Quality Rating[b]	Sample Size	Mean Age, y	Variables Associated With ACL Injury	Variables Not Associated With ACL Injury	Summary of Findings
Teng (2017)[45]	Fair	11 (11 M/0 F)	23.6	Toe-out landing	Toe-in landing, toe-forward landing	Toe-out landing position resulted in increased knee loading compared with toe-forward and toe-in positions.
Teng (2020)[46]	Fair	13 (13 M/0 F)	23.3	Flat-foot landing	Forefoot landing	Flat-foot landing, increased ACL injury risk, and forefoot landing decreased ACL injury risk.
Uebayashi (2019)[47]	Fair	28 (0 M/28 F)	20.5	Hip internal rotation angle, trunk rotation angle, knee flexion	NR	Decreases in hip internal rotation, knee flexion, and trunk rotation increased ACL loading.
Ueno (2021)[48]	Fair	13 (0 M/13 F)	15.6	Knee abduction, internal tibial rotation, anterior tibial translation, pelvic tilt, hip adduction	NR	Increased knee abduction, internal tibial rotation, anterior tibial translation, lateral pelvic tilt, and hip adduction were associated with increased ACL loading.

[a]All 22 studies on ACL loading were cross-sectional studies. ACL, anterior cruciate ligament; F, female; M, male; NR, not reported; ROM, range of motion.
[b]Study quality was categorized as good, fair, or poor.

TABLE 2
Characteristics of Studies on ACL Injury Outcomes (n = 6)[a]

Lead Author (Year)	Quality Rating[b]	Sample Size	Mean Age, y	Variables Associated With ACL Injury	Variables Not Associated With ACL Injury	Summary of Findings
Collings (2022)[7]	Good	322 (0 M/322 F)	20.3	Lateral trunk flexion	NR	Ipsilateral trunk flexion was predictive of increased risk of ACL injury.
Dix (2020)[11]	Good	51 (0 M/51 F)	19.6	Hip abduction angle	NR	Increased peak hip abduction angle was associated with an increased incidence of ACL injury.
Leppänen (2020)[24]	Good	258	16	Contralateral pelvic hike	NR	Increased contralateral pelvic hike was associated with noncontact ACL injury risk.
Nilstad (2023)[29]	Good	880 (0 M/880 F)	21.5	None	Lateral pelvic tilt, frontal plane knee projection angle, medial knee position	None of the tested variables were able to discriminate between injured and noninjured participants.
Räisänen (2020)[35]	Good	364 (187 M/177 F)	NR	None	Lower extremity alignment	Lower extremity alignment was not associated with ACL injury incidence.
Tainaka (2014)[44]	Fair	173 (99 M/74 F)	28.1	Limited hip ROM	NR	Limited hip rotation ROM was associated with increased incidence ACL injury.

[a]Five of the 6 studies on ACL injury outcomes were cohort studies; Tainaka et al[44] was a case-control study. ACL, anterior cruciate ligament; F, female; M, male; NR, not reported; ROM, range of motion.
[b]Study quality was categorized as good, fair, or poor.

TABLE 3
Quantitative Summary of ACL Risk Factors[a]

Risk Factor	ACL Loading Risk, % (No. of Studies)		ACL Injury Risk, % (No. of Studies)	
	Associated	Not Associated	Associated	Not Associated
Upper body biomechanics	83% (5/6)	17% (1/6)	100% (1/1)	0% (0/1)
Trunk extension/flexion	100% (5/5)	0% (0/5)	100% (1/1)	0% (0/1)
Upper trunk perturbation	100% (1/1)	0% (0/1)	NR	NR
Arm position	0% (0/1)	100% (1/1)	NR	NR
Hip biomechanics	83% (10/12)	17% (2/12)	100% (3/3)	0% (0/3)
Hip abduction/adduction angle	67% (2/3)	33% (1/3)	100% (1/1)	0% (0/1)
Hip internal rotation angle	100% (4/4)	0% (0/4)	NR	NR
Hip ROM	NR	NR	100% (1/1)	0% (0/1)
Hip flexion/extension	100% (3/3)	0% (0/3)	NR	NR
Pelvic tilt	50% (1/2)	50% (1/2)	100% (1/1)	0% (0/1)
Foot and ankle biomechanics	69% (9/13)	31% (4/13)	NR	NR
Foot-trunk distance	100% (1/1)	0% (0/1)	NR	NR
Toe-out landing	67% (2/3)	33% (1/3)	NR	NR
Toe-in landing	67% (2/3)	33% (1/3)	NR	NR
Toe-neutral landing	0% (0/1)	100% (1/1)	NR	NR
Forefoot landing	50% (1/2)	50% (1/2)	NR	NR
Flat-foot landing	100% (1/1)	0% (0/1)	NR	NR
Ankle plantarflexion angle	100% (1/1)	0% (0/1)	NR	NR
Ankle dorsiflexion ROM	100% (1/1)	0% (0/1)	NR	NR
Knee biomechanics	100% (5/5)	0% (0/5)	0% (0/2)	100% (0/2)
Knee flexion angle	100% (4/4)	0% (0/4)	NR	NR
Knee abduction/adduction angle	100% (1/1)	0% (0/1)	NR	NR
Medial knee position	NR	NR	0% (0/1)	100% (1/1)
Lower extremity alignment	NR	NR	0% (0/1)	100% (1/1)

[a]Values in parentheses represent the number of studies within each section of the table. ACL, anterior cruciate ligament; NR, not reported; ROM, range of motion.

data collection. In each study, an optical motion capture system with retroreflective markers was used to gather 3-dimensional kinematic data and develop a whole-body model. Participants in the cross-sectional studies performed a series of jumps and cutting tasks (eg, 1-leg side-cutting and single- or double-leg drop vertical jump tasks). Data from all the tasks were measured on landing. Associations between biomechanical variables and changes in ACL loading were reported for cross-sectional studies. The case-control study focused on assessing changes in injury risk by comparing hip range of motion (ROM) between injured versus noninjured participants.

Variables Associated With ACL Injury Risk

Quantitative metadata of the included articles can be found in Table 3. From the extracted data, the most common upper body factors related to increased ACL injury risk were increased trunk extension,[10,37,39] decreased trunk flexion,[15,37,39] and increased lateral trunk flexion.[7,17,37] Additionally, 1 study[43] found that midflight trunk perturbation increased ACL loading during landing. The sole article investigating the impact of arm position, by Chi-Yin et al,[6] found no association between any of the positions and knee loading during landing.

Hip kinematics were also important predictors of ACL injury. Four studies[15,18,42,47] found increased hip internal rotation angle to predict knee loading during landing and cutting. Additionally, increased hip abduction angle[11,42] and decreased range of hip flexion[27,33] and extension[9] during landing were significant risk factors. In 1 cohort study,[24] contralateral pelvic hike was associated with increased ACL injury incidence. The sole case-control study (Tainaka et al[44]) identified limited hip ROM as a risk factor.

Regarding foot and ankle biomechanics, the toe-out landing pattern was identified as a risk factor in 3 studies.[20,38,45] One study[14] found flexed knee dorsiflexion ROM of the ankle joint to be associated with an increased risk of ACL injury. Additionally, decreased ankle dorsiflexion ROM was associated with increased ground-reaction forces during landing. Increases in ankle plantarflexion angle,[23] internal tibial rotation, and anterior tibial translation[48] were also identified as risk factors.

Knee-related biomechanical variables associated with ACL injury included decreased knee flexion angle,[13,33,41,47] increased knee flexion excursion,[41] and increased internal tibial rotation and anterior tibial translation.[48] The most recent cohort study found no association between ACL injury and lateral pelvic tilt, frontal plane knee projection angle, or medial knee position.[29]

There were several conflicting findings within the extracted data. For instance, forefoot landing was identified as a risk factor for ACL injury in one study,[8] but another study found it not to be associated.[46] Similarly, there were discrepancies in the impact of hip abduction, with 2 studies[11,42] identifying it as a risk factor, while another study[9] found no such association. Finally, there was conflicting evidence for pelvic tilt as a risk factor, with 1 cross-sectional study[48] supporting it and 1 longitudinal study[29] finding no association.

DISCUSSION

In the current systematic review, we sought to integrate and articulate the existing knowledge of biomechanical risk factors implicated in ACL injuries. Notable among the risk factors identified were decreased knee flexion angle, increased hip internal rotation angle, contralateral pelvic hike, toe-in position, lower ankle dorsiflexion ROM, decreased ankle plantarflexion angle, and trunk positions such as increased trunk extension and increased lateral flexion. These factors were recurrently cited across multiple studies included in this review.[‖] These findings are supported by a systematic review performed by Larwa et al[22] in 2021. They observed that stiff landings (measured as decreased ankle dorsiflexion and reduced knee flexion), poor core stability influencing trunk angle and lean, and weakness in hip abduction, which contributes to increased hip internal rotation angles, were all identified as risk factors for ACL injuries in male and female athletes.

Misalignment of the trunk in particular can significantly affect lower limb biomechanics, including knee positioning. When the trunk leans excessively to one side, defined by Leppänen et al.[24] to be a contralateral pelvic hike of 13° or more during landing, it can lead to an increased knee valgus and internal rotation of the tibia. These aberrant knee biomechanics can result in an elevated load on the ACL. The ACL is primarily responsible for restraining anterior tibial translation and rotational loads[12]; thus, any abnormal knee positioning that increases rotational forces or anterior shear forces can heighten the strain on this structure. Additionally, any disturbances in the kinetic chain that affect the knee could further contribute to the inappropriate loading of the ACL, escalating the risk of injury. As mentioned above, a misaligned trunk may alter the distribution of forces throughout the distal aspect of the kinetic chain, or excessive hip internal rotation may cause the knee to favor a position of increased valgus stress. One of the principal injury mechanisms recognized among these risk factors is uncontrolled knee loading during dynamic tasks. Activities such as landing from a jump or executing cutting maneuvers often precipitate high forces and torques around the knee joint,[49] resulting in forces that can surpass the load-bearing capacity of the ACL, increasing risk of injury.[14,20,41,45]

‖References 7, 10, 13, 14, 18, 20, 23, 24, 27, 33, 37-39, 41, 47, 48.

It is crucial to note that not all variables studied were found to be associated with ACL injury. Factors like lateral pelvic tilt, frontal plane knee projection angle, medial knee position, lower extremity alignment, and arm position were not consistently related to ACL injury across the reviewed studies. Although arm position has been shown to influence knee valgus moment in some studies,[5,16] there is a lack of consensus and sufficient evidence to conclude whether arm position has an impact on ACL injuries, as shown in the current review. Additionally, medial knee position and lower extremity alignment were each only evaluated in 1 study. The results of the study conducted by Nilstad et al[29] were contradictory to the already well-established theory that a knee positioned in valgus is at higher risk of ACL injury[19]; however, the authors evaluated medial knee position as a static measure, which could explain the discrepancy with the preexisting assumption. The dynamic relation of the kinetic chain bridging the ankle, knee, hip, and trunk is complex, with factors affecting this chain previously having been identified as risk factors for ACL injury.[27] Hence, although not all the aforementioned factors were related to increased risk of ACL injuries in our study, we cannot disregard them as being important considerations for athletes.

Understanding biomechanical risk factors is essential for developing targeted interventions and training programs to prevent ACL injuries. An example of such a program is the Fédération Internationale de Football Association (FIFA) 11 +, which focuses on strength, balance, and plyometric exercises to engage supporting muscles around the joints through neuromuscular training and has proven to be an effective prevention program for lower extremity injuries in soccer players.[2] It might be beneficial to incorporate exercises that target identified risk factors into preventative athletic training programs. For example, the FIFA 11 + has shown minimal effect on some factors identified in this review, such as ankle dorsiflexion ROM.[1] Modifying the training program to incorporate calf stretches or other preventive exercises specific to each athlete may improve outcomes.[34]

Additionally, identifying ACL injury risk factors can enhance the training of machine learning software, facilitating the development of predictive video analysis tools.[26] By incorporating newly identified risk factors, such as toe-in position, increased hip internal rotation angle, increased lateral pelvic tilt, and specific ankle angles (eg, lower ankle dorsiflexion ROM and decreased ankle plantarflexion angle), these models can concentrate on essential variables, thereby refining their focus.[21] The challenges that sports medicine professionals face in predicting knee injuries based solely on visual assessments were highlighted in a cross-sectional study by Mørtvedt et al[28] that underlines the invaluable role of machine learning models in this domain.

Limitations

Some limitations to this review must be noted. The included research predominantly consisted of cross-sectional studies with relatively small sample sizes, which restricted the strength of causal inferences that could be drawn. Second, there was a notable lack of longitudinal studies, which are superior to cross-sectional designs for establishing causality and assessing the progression and impact of biomechanical risk factors over time.[4] Finally, it is important for clinicians and patients to be aware that ACL injury risk is multifactorial and not solely determined by biomechanical factors[32]; thus, a comprehensive approach is needed in the prevention and management of ACL injuries.

CONCLUSION

Our systematic review found the biomechanical risk factors with the greatest supporting evidence to be decreased knee flexion angle, increased hip internal rotation angle, contralateral pelvic hike, toe-in position, lower ankle dorsiflexion ROM, decreased ankle plantarflexion angle, and trunk positions such as increased trunk extension and increased lateral flexion. Future research should continue to explore these biomechanical risk factors, particularly those lacking or with conflicting evidence. Additionally, longitudinal studies evaluating these risk factors are necessary to increase the strength and reliability of causal relationships between the variables. Ultimately, this research can play a role in reducing the incidence and impact of ACL injuries, improving the long-term health and quality of life for athletes and physically active individuals alike.

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