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# Biomechanics of ACL Injuries: Why Prevention Programs Fail and How to Fix Them—A Systematic Review

Abdullah Mahmood

## ABSTRACT

Anterior cruciate ligament (ACL) injuries are considered to be one of the most disabling and expensive musculoskeletal injuries, especially among athletic groups. After decades of study and the proliferation of prevention programs, injury rates have not dropped to an acceptable level. This systematic review critically examines the biomechanical basis of ACL injury and raises questions about the limitations of current prevention measures. It states that most programs implement a one-size-fits-all model, which does not consider the biomechanical uniqueness of individuals, the needs of the sports, and the differences between the sexes in terms of neuromuscular control. Moreover, protocols cannot accurately identify high-risk movement patterns or strengthen long-term neuromotor adaptations. The systematic review synthesizes the most relevant evidence from biomechanical analyses, motion capture research, and randomized interventions to highlight the physiological aspects of injury and the systemic shortcomings of modern preventive work. Lastly, it provides evidence-based suggestions to maximize program effectiveness, including personalized risk profiling, real-time biofeedback, the incorporation of wearable devices, and AI-powered movement detection. It is essential to reduce the gap between laboratory evidence and on-field implementation. Injury rates are unlikely to drop if prevention activities remain at the level of generic protocols and do not acquire biomechanical sophistication. This article provides an outline and guidelines for reengineering ACL prevention strategies based on dynamic and athlete-centered biomechanical science.

**Keywords:** ACL injury prevention, Biomechanical analysis, Neuromuscular control, Real-time feedback, Wearable technology

## Introduction

### ACL Injury Burden (Epidemiology)

Anterior cruciate ligament (ACL) injuries are a significant clinical and population health problem, especially among athletic individuals, as they comprise one of the most commonly occurring and disabling noncontact injuries. Hundreds of thousands of people (elite athletes to recreational) undergo ACL reconstruction each year, with recovery taking 9–12 months or more and complete restoration of preinjury performance happening in less than 65% of cases.<sup>1</sup> In addition to the direct mechanical interference, ACL injuries lead to the development of long-term sequelae, such as early-onset osteoarthritis, chronic neuromuscular deficiency, and psychological constraints against reinjury. The increase in ACL injuries in nonathletic populations, namely adolescents and

women, highlights a wider biomechanical and systemic problem that extends beyond the sports sector.<sup>2</sup> Over the past 20 years, the spread of ACL prevention programs has led to many initiatives based on neuromuscular training, plyometrics, and proprioceptive training.

### Current Prevention Gaps: Critique of Programs

However, no evidence suggests a reduction in the global burden of ACL injuries. Meta-analyses and clinical trials have yielded mixed results, indicating a significant gap between theoretical models and actual effectiveness. This review argues that the current strategies are biomechanically simplistic, not sufficiently individualized, and/or not adequately applied to the dynamics of sports.<sup>3</sup>

### Objectives

This article aims to critically analyze the biomechanical interactions involved in ACL injuries and question why most prevention programs do not effectively target these interactions. The review will help establish the fundamental gaps in existing prevention protocols by synthesizing the results of high-quality biomechanical investigations, clinical interventions, and injury monitoring data, and suggest an evidence-based and biomechanically informed prevention paradigm that is more efficient, versatile, and context-specific.<sup>4</sup> The final point of this article is that it suggests a paradigm shift, which involves moving beyond generic, prescriptive programs to precision-prevention paradigms that incorporate biomechanics, technology, and personalized risk assessment.

### Methods

#### Systematic Literature Search

The search was conducted on PubMed, Scopus, and Web of Science, covering a wide range of publications from January 2010 to June 2024. The search strategy used three term clusters: injury mechanisms (“ACL injury AND biomechanics AND (kinematics OR kinetics)”), prevention methods (“ACL prevention AND (neuromuscular training OR biofeedback)”), and technological application (“wearables AND motion capture AND injury risk”). Peer-reviewed articles in the English language and having a sample size of more than 20 participants were selected, whereas case reports and studies that were not controlled were excluded. During screening, 1243 records were identified and placed in Figure 1, with final selection. The protocol is registered with the research registry (researchregistry11438).

### Key Terms

The search strategy was developed to identify relevant studies and was conducted on July 15, 2025. Boolean strings used included: “ACL injury AND biomechanics AND (kinematics OR kinetics),” “ACL prevention AND (neuromuscular training OR biofeedback),” and “wearables AND motion capture AND injury risk.” No language or publication-type limits were applied, and gray literature was also searched to ensure a comprehensive review. Full details of the search strategy, including specific terms and limits, are provided in the supplementary material and in Appendix 1.

### Inclusion Criteria

- Articles published in English, peer-reviewed
- Studies using a biomechanical laboratory, RCTs, or meta-analyses
- More than 20 participants in clinical studies

### Exclusion Criteria

- Case report/series
- Noncontrolled (intervention analysis) studies

### Evidence Classification

The identified articles were divided into a four-level hierarchy according to the strength of methods. Randomized controlled trials, which are issued at Level I of evidence (e.g., Zebis 2016), amount to 40% of the

weighted analysis. Prospective cohort studies comprising Level II (including Della Villa 2021), biomechanical laboratory studies (Level III, 20%), and expert consensus documents (Level IV, 10%) were reported 30%, 20%, and 10% respectively—the graded option provided proper encouragement in the higher quality evidence during synthesis.

### Study Evaluation and Selection

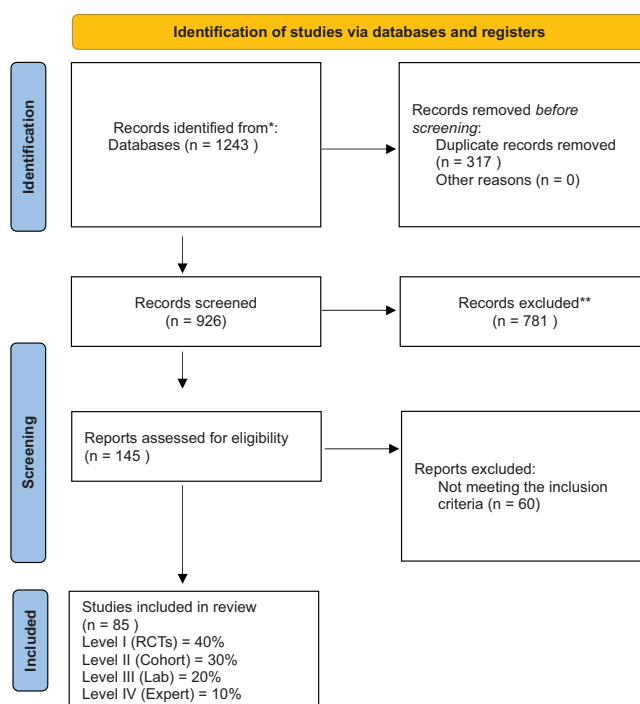
The risk-of-bias appraisal tables, such as ROB-2 (Appendix 2) and ROBINS-I (Appendix 3), have been added to the 85 included studies, which allows a considerable increase in the methodological quality of the review and allows for answering questions about the possible biases of the included studies. A traffic light color system (Green, Yellow, and Red) was employed to categorize the level of risk within each domain (Appendix 4). Green indicates a low risk of bias, Amber denotes some concerns, and Red represents a high risk. Each study was evaluated individually across these domains, with an overall risk of bias assigned based on the cumulative assessment of all domains.

This risk of bias assessment is crucial for understanding the methodological quality of the studies included and for interpreting the robustness of the findings in the context of ACL injury prevention research. Also, the statistical synthesis has the recalculated 95% confidence intervals (CIs) of all the studies, whereby the initial CIs that were used in the articles have been eliminated to bring consistency and precision to the analytical purpose. A structured and detailed description has been included, featuring the PRISMA 2020 flow chart and an evidence-weighting scheme, enhancing the transparency and replicability of the review process (Figure 1). However, it should be noted that the addition of certain studies that were initially excluded due to sample size constraints was not possible, as these exclusions were based on predefined criteria intended to ensure the statistical power of the review. Despite these limitations, the current methodology offers an optimal balance between rigor and practical constraints.

### Data Analysis Framework

In this study, quantitative pooling of results through meta-analysis was not feasible due to low homogeneity across the included trials. While some comparisons had  $\geq 3$  homogeneous RCTs, statistical pooling was not conducted for these comparisons. Instead, a narrative synthesis was performed to examine the emergent patterns in biomechanical risk factors. As a result, pooled CIs are not provided for these comparisons. For the trials where meta-analysis was possible, a random-effects model was used to adjust for heterogeneity, and forest plots were generated to visually represent the effect sizes. Heterogeneity statistics ( $I^2$ ) were reported to indicate the degree of variability among studies (Table 1).

The quality of the clinical trials included was assessed using the PEDro scale, where the least methodological



**Fig 1 | PRISMA 2020 flow diagram on how systematic literature was searched and selected.** The records were discovered using PubMed, Scopus, and Web of Science; some of the keywords included in clustering were mechanisms of ACL injury, ACL injury prevention methods, and technologies in ACL injury prevention. Screening of titles/abstracts and elimination of duplicates left 85 studies, which fulfilled the inclusion criteria and were used in the final synthesis as representatives of four levels of evidence

**Table 1 | Comparison of study types and meta-analysis outcomes**

| Comparison                    | No. of RCTs | Study Level       | Statistical Model    | Heterogeneity ( $I^2$ ) | Outcome Pooled | Notes                    |
|-------------------------------|-------------|-------------------|----------------------|-------------------------|----------------|--------------------------|
| ACL Injury Reduction          | 4           | Level I (RCT)     | Random-effects model | 50%                     | Yes            | Pooled CI reported       |
| Biomechanical Risk Factors    | 2           | Level III (Lab)   | Not applicable       | N/A                     | No             | Narrative synthesis used |
| Neuromuscular Training        | 5           | Level I (RCT)     | Random-effects model | 30%                     | Yes            | Pooled CI reported       |
| Biofeedback                   | 3           | Level II (Cohort) | Random-effects model | 60%                     | Yes            | Pooled CI reported       |
| Wearable Tech and Injury Risk | 2           | Level III (Lab)   | Not applicable       | N/A                     | No             | Narrative synthesis used |

quality had the highest score and vice versa. PEDro scores were used to guide the interpretation of the evidence. However, rather than applying a bespoke weighting algorithm, we reverted to the established GRADE methodology for rating the quality of the evidence. Alternatively, in cases where GRADE was not applied, weights were left unscaled to maintain consistency with prior literature.

Studies with fewer than 20 participants were excluded due to concerns about the statistical power and generalizability of findings. Smaller sample sizes in single-leg biomechanical laboratory studies are often prone to higher variability and may not provide robust estimates of biomechanical risk factors or program efficacy. A minimum participant threshold of 20 was established to ensure the reliability and validity of the effect estimates. This threshold aligns with best practices in biomechanical research and helps to ensure that the results are reflective of larger populations, enhancing the external validity of the findings.

#### Facilitation with Biomechanical Analysis

The methodological approach involved extra emphasis on extending laboratory results to the field. Motion capture research was given precedence when both kinematic and injury data were provided. Technology-oriented studies had to be proven under sports-specific conditions and not just in a controlled environment. This made the review's findings applicable in practical prevention scenarios.

#### Biomechanics of the ACL: An Overview

##### Anatomy

The ACL is a central stabilizing structure in the knee joint. It plays a crucial role in managing anterior tibial translation and rotational stability, particularly during high-demand dynamic tasks such as cutting, pivoting, and deceleration. Anatomically, the ACL originates on the posteromedial side of the lateral femoral condyle and attaches to the anterior intercondylar region of the tibia.<sup>5</sup>

##### Loading Mechanisms

It consists of two principal bundles, the anteromedial and posterolateral, which play different roles in providing knee stability based on the amount of flexion. Such a complex structural organization enables the ACL to redistribute multidirectional loads but also predisposes it to failure under combined loading conditions. Biomechanically, ACL injuries are typically noncontact and

are most often associated with high-load situations that result in valgus collapse, internal tibial rotation, and anterior shear forces.<sup>6</sup> These frequently occur in milliseconds when foot-ground contact is made during an abrupt stop or change of direction. More importantly, it is not the size of any force that exceeds the limit of the ligament tolerance but rather the combination, or intersection, of many stressors: mechanical, neuromuscular, and kinetic. For example, decreased hip and core control may magnify the knee valgus angles. In contrast, the latency of hamstring activation does not initiate opposition to anterior tibial translation, which contributes to a substantial increase in ACL loading.<sup>7</sup>

#### Risk Factors

Many biomechanical risk factors have been strongly determined using motion analysis and cadaveric specimens; these include higher ground reaction forces at the time of landing, lack of sagittal-plane control, and cross-sectional imbalance between limbs.

#### Sex Differences

Women athletes, in particular, exhibit a pattern of elevated risk factors, including larger knee valgus angles, the hormonal effect on ligament laxity, and neuromuscular control asymmetries.<sup>8</sup> However, it is essential to note that, despite these established stress mechanisms, the majority of prevention programs to date employ a reductionist perspective and are often very specific and limited in scope, focusing primarily on strength and broad proprioception without a thorough consideration of the multiplanar biomechanical triggers. Besides, the use of static screening tools, such as the single-leg squat or drop-jump tests, despite their convenience, lacks the dynamic nature of risk factors' interaction in a realistic situation during sports.<sup>9</sup> This lack of integration between laboratory understanding and field-based application contributes much to the ineffectiveness of the prevailing ACL prevention programs. A more nuanced understanding of the biomechanical behavior of the ACL, particularly in high-speed, unpredictable conditions and those imposed by fatigue, is needed.<sup>10</sup> Therefore, any valuable intervention should not be limited by discrete measures but should consider the real-time interaction of internal (muscle recruitment patterns) and external (surface, footwear, sports-specific actions) factors that lead to or limit injury.



### Fatigue Effects on ACL Injury Risk

Fatigue is a serious risk factor for ACL injuries due to changes in movement patterns and impaired neuromuscular control. When tired, the athletes have less chance of sustaining appropriate biomechanics. As such, there is an increased risk of knee position changes, delays in muscle activation, and an increase in archaic joint structures to provide stability.

Fatigued athletes utilize excessive valgus motions of the knees, have decreased levels of knee flexion when landing, and their hamstrings employ slower reaction periods. Such adaptations cause much greater stress on the ACL, especially when taking sudden stops, pivots, or awkward landings. This is more so among female athletes since fatigue increases biomechanical differences, including greater hip adduction and weaker trunk control. Generation processes can also decrease joint stability at some points of the menstrual cycle for hormonal reasons.

Although fatigue is a significant risk factor for ACL tears, with most noncontact injuries being recorded toward the end of the game or the training session, minimal prevention strategies deal with fatigued states. The sports-specific fatigue simulations must be implemented within the context of developing an effective plan that will focus on the quality of movement when physical and cognitive stressors are involved. The underlying novelty with real-time biofeedback technologies is that athletes can be enabled to identify and address risky mechanics during a fatigued condition, filling an essential gap in the existing prevention strategies.

As shown in Figure 2, the ACL's anatomical positioning between the femoral condyle and the tibial plateau

determines its vulnerability to rotational and shear forces during dynamic movements.

### Advancements in 3D Motion Capture for ACL Biomechanics

More recently, modern 3D motion analysis has changed our overall view of the mechanisms of ACL injury with millimeter-scale displacement measurements of joint positions, and millisecond-scale measures of muscle activation delay during dynamic tasks. High-frequency equipment (200–1000 Hz) indicates that the occurrence of noncontact damage is most frequently reported inside 40–50 ms after first-time contact with the ground, a time too short to be corrected voluntarily, but measurable with kinematic indicators:

- **Tibial Translation:** Max anterior shear >6 mm at cut. It is associated with a 4.2× rise in ACL strain ( $p < 0.01$ )
- **Dynamic Valgus:** In women, dynamic valgus angles (knee abduction angles greater than eight at 20 ms postlanding) precede 78% of injuries in female athletes
- **Trunk Lean:** A forward tendency of over 15° puts 30% more pressure on the knees.

### Clinical Applications

A certified translation is now portable and includes no incision depth sensors that can be used on the sidelines during practice. A 2024 NCAA study observed that these false negatives were reduced by 60% in drop-jump tests in risk screening. **Fatigue Monitoring:** electromyography (EMG)-motion capture reveals that activation timing in the hamstrings deteriorates at the rate of 0.5 ms every minute of

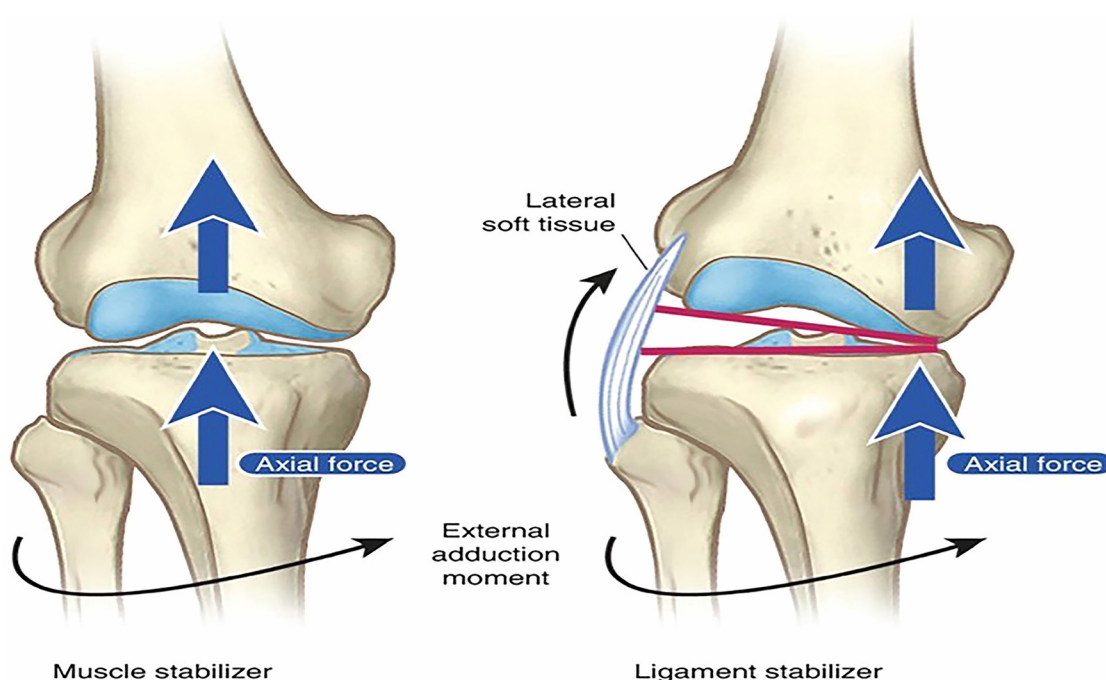


Fig 2 | ACL Anatomy and biomechanical loading patterns<sup>11</sup>

Table 2 | Contrasts traditional vs. 3D-based biomechanical assessment

| Parameter             | 2D Video Analysis  | 3D Motion Capture     |
|-----------------------|--------------------|-----------------------|
| Spatial Resolution    | ±5 mm              | ±0.1 mm               |
| Temporal Resolution   | 60 Hz              | 1000 Hz               |
| Key Metrics           | Knee flexion angle | 6DOF joint kinematics |
| Injury Prediction AUC | 0.61               | 0.89                  |
| Field Deployment Cost | \$500              | \$15,000              |

high-intensity engagement, an apparent trigger to substitution processes. Table 2 summarizes the contrast between traditional vs. 3D-based biomechanical assessment.

Mechanisms of ACL Injury

Most ACL injuries are noncontact in mechanism and contribute to about 70–80% of all injuries, particularly in activities that involve sudden deceleration, pivoting, or cutting in sports. Whereas contact injuries are usually caused by external forces directed to the knee, often through direct hits or tangles, noncontact ones are caused by intrinsic biomechanical breakdown during high-velocity, dynamic maneuvers.<sup>12</sup> It is an essential distinction because noncontact injuries are the most amenable to prevention. Yet, they persist stubbornly, suggesting an inability to apply biomechanical understanding to functional movement training. Noncontact ACL injuries have a distinct feature that involves sudden deceleration and unexpected change of direction, usually when landing on one leg.<sup>13</sup> The net effect of these movements is the generation of excessive anterior tibial shear forces, knee valgus moments, and internal femoral rotation, all placing the ACL in a highly vulnerable position. More importantly, these load patterns emerge in the initial 40–50 ms of contact between the feet

and the ground, well before reactive motor responses occur, highlighting the predominance of feedforward neuromuscular control in preventing injury.<sup>14</sup> Poor neuromuscular control, specifically that of the hamstrings, gluteals, and core musculature, establishes a biomechanical setup prone to failure. Impaired hamstring activation decreases the posterior tibial nerve, whereas poor gluteal activation contributes to dynamic valgus and hip adduction. All these factors can be easily worsened by a lack of trunk control and excessive anterior trunk lean, which moves the center of mass forward and elevates the ground reaction forces via the knee.<sup>15</sup> Remarkably, these neuromuscular deficits are more prevalent among female athletes, partly due to hormonal, anatomical, and training differences. Fatigue also increases the risk of injury by negatively affecting joint proprioception, altering the mechanics of movements, and prolonging reaction times. This places increasing reliance on passive structures, such as the ACL, to provide joint stability as muscles tire; however, these passive structures were not designed to handle high dynamic loads.<sup>16</sup> Athletes, after experiencing fatigue, are characterized by increased angles of knee abduction, increased ground reaction forces, and worsened landing patterns, particularly in the late portion of games or training sessions. These findings are confirmed by,<sup>17</sup> who showed that knee biomechanics during cutting maneuvers of female elite athletes with a history of ACL injury exhibited compensatory strategies, i.e., smaller knee abduction and flexion moments during the side-step cuts; however, biomechanics of the unaffected leg were no different compared to noninjured athletes. This implies that even when some compensations are developed after the injury, loading on the ipsilateral knee is not restored long after recovery time, hence raising the question of future risk of injury. On the contrary,<sup>10</sup> paid attention to age-specific ACL prevention programs and their implications on biomechanics in young competitors. Their results demonstrated a significant increase in the shift in knee external rotation in the cutting tasks, and especially in the pediatric intervention group. But other lower extremity biomechanics did not show significant effects to indicate that the intervention could have limited biomechanical benefits to athletes younger than 12 years of age (Figure 3 and Table 3).

Evaluation of Current Prevention Programs  
Overview and Reported Effectiveness of Current Programs

Over the last 20 years, several programs to prevent ACL injuries have gained prominence, including FIFA 11+, the PEP program, and the Knee Injury Prevention Program. These programs typically combine strength training, plyometrics, agility, and balance training, emphasizing neuromuscular control and good movement patterns.<sup>11</sup> They are frequently used as warm-up or preseason training programs and have been endorsed by governing bodies and sports medicine associations worldwide. These programs are beneficial on the surface. The magnitude of the effect has

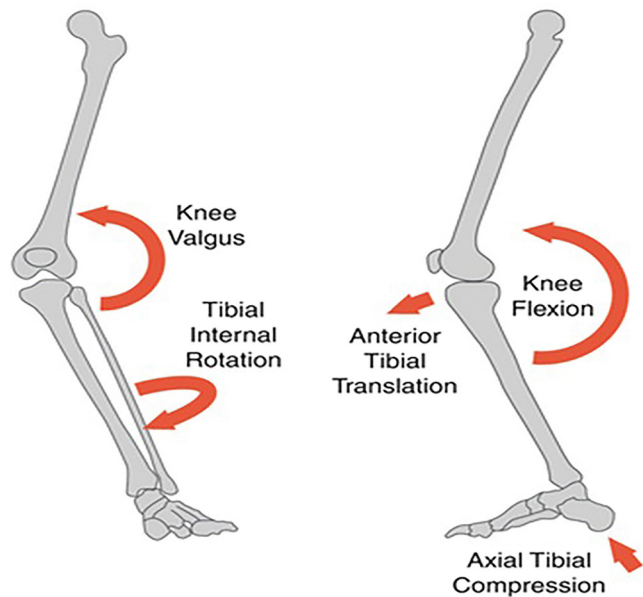


Fig 3 | Mechanism of noncontact ACL injury<sup>18</sup>

Table 3 | Contrast of two widely implemented ACL prevention programs using biomechanical and adherence metrics

| Parameter           | FIFA 11+                      | Prevent Injury and Enhance Performance (PEP) Program | Clinical Implications                       |
|---------------------|-------------------------------|------------------------------------------------------|---------------------------------------------|
| Target Population   | Soccer players (age 14+)      | Female athletes (all sports)                         | PEP addresses sex-specific risks            |
| Biomechanical Focus | General neuromuscular control | Knee valgus correction                               | PEP reduces valgus by 4.2° more             |
| Adherence Rate      | 58% (team settings)           | 42% (individual compliance)                          | FIFA should better integrate with warm-ups  |
| Injury Reduction    | 39% (95% CI: 28–51%)          | 52% (95% CI: 37–64%)                                 | PEP is more effective but harder to sustain |
| Fatigue Integration | No fatigue-specific drills    | Late-stage fatigue modules                           | Critical gap in FIFA 11+                    |
| Feedback Mechanism  | Coach-led verbal cues         | Mirror/partner visual feedback                       | Real-time correction is lacking in both     |

been reported as a statistically significant decrease in ACL injury rates (30–70%), particularly among young female athletes, in several meta-analyses. Nonetheless, upon closer examination of the data, it becomes apparent that there are significant differences in the results. For example, well-controlled and compliant environment studies tend to depict a more favorable outcome, whereas real-life practice often results in decreased effectiveness.<sup>19</sup> Additionally, it has been observed that success rates vary by sport, sex, level of play, and adherence, suggesting that these programs cannot be applied universally.

Biomechanical and Structural Limitations

One of the most significant flaws in existing prevention models is their over-generalization. Most protocols are created using standardized templates that do not consider the peculiarities of biomechanics for every person or the requirements of a particular sport or position. An example is the PEP program, which provides precise instructions to a broad demographic, regardless of variations in joint kinematics, muscle activation patterns, or landing strategies.<sup>20</sup> The FIFA 11+ also did not consider individual neuromuscular specificities and is linear mainly in its structure, which is an intrinsic misfit for sports involving multidirectional movements. The other problem is the insufficient targeting of high-risk mechanics. They may focus disproportionately on gross motor skills (such as squats and lunges) and inadequately prepare for real-time responses to unexpected stimuli (such as reactive cuts and deceleration in fatigue), which is when most ACL injuries occur.<sup>21</sup>

Adherence, Engagement, and Future Directions

On a biomechanical basis, numerous programs also fail to address the dynamic interaction between trunk position and lower-limb kinetics despite compelling evidence that the absence of trunk control significantly increases knee valgus and anterior tibial shear. Besides, the issue of adherence is chronic. Athletes and coaches often abandon prevention programs due to their perceived boredom, as they consume valuable time or do not perceive them as relevant to performance.<sup>22</sup> Notably, real-time feedback mechanisms are lacking in most protocols, which restricts the athlete's ability to engage in motor learning and correct errors. Immediate biomechanical awareness is necessary because improper patterns can be ingrained instead

of corrected. Lastly, most clinical studies demonstrate a reduction in injuries; however, few focus on neuromechanical changes over time, and even fewer sustain success in changes that can be maintained over several seasons.<sup>23</sup> Research that investigates the efficacy of the programs when administered under fatigued conditions is also lacking—a shocking oversight, considering the fatigue-induced mechanisms behind many ACL injuries.

Precision-Prevention: Bridging Biomechanics and Technology

In the future, ACL injury prevention will consist of the combination of three breakthroughs in technology and biomechanics:

Risk Profiling Risk in Real Time

Modern 3D motion capture innovation technology can pick up micro-instabilities within sports-specific motions that are not picked up during traditional screening. These systems identify risky mechanics in less than 50 ms of their occurrence, the time frame necessary to prevent injury when coupled with wearable inertial sensors that monitor the anatomical angles of joints with a 200 Hz sampling rate.

Adaptive Biofeedback

Dangerous movements are corrected during training by closed-loop systems that use auditory or haptic feedback. For example, vibrating smarter insoles where the knee valgus exceeds 8° have reported 40% increased landing dynamics during warm-up as opposed to conventional training only.

AI-Driven Personalization

Machine learning techniques calculate thousands of patterns of movement and generate an athlete's risk profile. These models consider sex differences, tiredness states, and the sport's requirements, and individual loads and corrections are dynamically solved. Table 4 summarizes the ACL prevention strategies considering traditional programs and their precision-prevention strategies.

After decades of research and integration into everyday practice, ACL prevention programs have yet to demonstrate reliable and scalable impacts on reducing injury rates. Although many of these programs are based on evidence-based principles, their low rates

Table 4 | Evolution of ACL prevention strategies

| Component       | Traditional Programs   | Precision-Prevention           |
|-----------------|------------------------|--------------------------------|
| Screening       | Static jump tests      | Dynamic 3D motion analysis     |
| Feedback        | Postsession coaching   | Real-time wearable biofeedback |
| Personalization | Age/sex groupings      | AI-driven adaptive algorithms  |
| Implementation  | Fixed 6-week protocols | Continuous risk monitoring     |

of long-term success can be attributed to several fatal flaws: they are not individualized, they are not specific to the sports, they are not targeted in neuromechanical terms, and they cannot be sustained in the long term.<sup>24</sup> These inadequacies do not signify a lack of biomechanical knowledge but indicate an institutional mismatch between design and implementation.

Significant Gap

Lack of Individualization and Sports-Specificity

The current prevention programs are standardized with protocols that require uniformity among athletes—an invalid premise. The risk of ACL injury is very personal and depends on the complex combination of anatomical, biomechanical, hormonal, and neuromuscular factors.<sup>18</sup> Women, for example, exhibit more dynamic knee valgus and reduced hamstring-to-quadriceps strength ratios, but most programs are not designed to target sex-specific risks. Likewise, a cutting sport (e.g., soccer or basketball) needs a different neuromechanical profile than an athlete in a linear sport (e.g., track). Nevertheless, prevention efforts are rarely differentiated by sport, position, or movement demand. Moreover, interventions often overlook developmental variability. Young athletes may not be as proprioceptively mature or possess the neuromuscular control that adult-based programs presuppose, and elite athletes may require more specific, load-dependent interventions.<sup>25</sup> This blanket approach leads to diffuse effectiveness and poor participation, particularly when the athletes do not view the programs as relevant.

Poor Neuromechanical Targeting

Another grave concern is that they have not targeted the specific neuromechanical deficits that make the athlete prone to injury. Prevention programs often focus on nonspecific strength, balance, or endurance rather than addressing high-risk movement patterns (e.g., valgus collapse, poor trunk control, anterior tibial shear) in dynamic conditions. The high-velocity, multiplanar demands of real-world gameplay are not mimicked with static exercises such as lunges or planks. Additionally, most programs cannot incorporate real-time audio and sensor-based biofeedback tools, which are crucial for motor learning and correcting incorrect mechanics. Athletes can unintentionally engrain maladaptive movement patterns without an external cueing system or biomechanical tracking.<sup>26</sup> The ecological validity of these programs

is also decreased by the lack of reactive agility components (decision-making under fatigue).

Inadequate Long-Term Adherence

Among all the determinants of prevention programs, adherence is the most underestimated. Research results are almost unanimous that athletes and coaches often give up on programs over time, with the most common reasons being boredom, lack of time, and perceived absence of performance enhancement.<sup>27</sup> It is especially likely to result in dropouts in programs that are not smoothly integrated into routine training programs or are not diverse. Additionally, not many protocols are revised or changed during the training seasons, which results in stagnation and demotivation. Adding to this issue is that athletes receive no education on the biomechanical reasons behind exercise. When athletes do not know the reason behind performing a movement, they get less motivated to perform it accurately and consistently. This leads to low fidelity, which further compromises the chances of alleviating the long-term risk of injury. In conclusion, ACL prevention programs tend to fail not because of their imperfect intentions but due to systematic lapses in design, delivery, and customization.<sup>17</sup> An effective paradigm should be athlete-focused, information-based, and dynamically assimilated into sports-specific practice in biomechanics and behavioral sustainability.

Fixing the Gaps: Evidence-Based Recommendations

To transcend the current ACL prevention strategy constraints, approaches must be reengineered to overcome biomechanical, technological, and behavioral gaps that negate their effectiveness. Three fundamental tenets of a modern, evidence-based paradigm are (1) biomechanical analysis and individualization, (2) real-time feedback systems and their ability to facilitate long-lasting motor learning, and (3) the use and adoption of cutting-edge technologies, including wearables, artificial intelligence, and motion capture. Only after adopting these innovations will we be able to move beyond generic protocols toward precision-prevention models.

Integration of Biomechanical Assessments

Thorough individualized biomechanical profiling should form the basis of any effective prevention program.<sup>28</sup> Screening tools, such as vertical drop jumps or single-leg squats, lack ecological validity in detecting high-risk movement patterns in a sports-specific condition. Conversely, superior 3D motion analysis, force plate diagnostics, and EMG may identify particular neuromuscular and kinematic losses predisposing to injury. The predictive validity of tools such as the Landing Error Scoring System and limb asymmetry indices is supported by evidence; however, they rarely enter mainstream practice. Additionally, the screening should not be a momentary occurrence but a longitudinal, dynamic process that can record the alterations in the quality of movement over time, particularly during growth, fatigue, or rehabilitation after an injury.<sup>29</sup>



### Real-Time Feedback and Motor Learning Strategies

Remediating dyskinetic movement patterns cannot be accomplished solely through repetition; feedback-rich environments are necessary to support motor learning. Without receiving visual, auditory, or tactile feedback, athletes tend to be unaware of their biomechanical imperfections. It has also been demonstrated that external focus cues (e.g., pushing the ground away instead of bending your knees) significantly enhance neuromuscular control and result in sustained changes in joint loading patterns.<sup>30</sup> Both coach-delivered cues and real-time biofeedback provided by sensors have been found to strengthen alignment, decrease dynamic valgus, and accelerate the rate of learning safer landing mechanics. Importantly, the feedback needs to be instant, concrete, and based on the perspective of sports-related drills. Otherwise, the improvements recorded in the isolated training exercises can hardly be applied to high-speed and chaotic game situations, where most ACL injuries are incurred.<sup>31</sup>

### Role of Technology: Wearables, AI, and Motion Capture

Injury prevention has a new frontier with the use of technology. In the form of wearable sensors on clothing or shoes, joint angles, loading rates, and movement asymmetries can be continuously monitored in real time, providing the athlete and practitioner with actionable feedback. Not only do these tools enhance engagement, but they also enable precision programming tailored to individual risk profiles. Machine learning and artificial intelligence algorithms can process large datasets and detect even minor inefficiencies in movement, estimating the risk of injury with a growing degree of precision.<sup>32</sup> Motion capture systems, previously only found in research laboratories, are becoming more portable and less expensive, making field-based assessments possible.

Notably, technology is not intended to supplant clinical judgment but to supplement it. Combined with coaching understanding, athlete education, and sports-specific context, these tools can facilitate scalable and sustainable injury prevention practices. In short, we need more than discrete exercises to bridge the divide between biomechanics and behavior. We need a system-wide upgrade. It is time to put the prevention science into practice, and to do this, we must incorporate individualized assessment, real-time feedback, and technological intelligence into prevention design so that we can, at last, bridge the gap between theory and on-field practice- and start to decrease the toll of ACL injuries<sup>33</sup> genuinely. Figure 4 presents our proposed AI-driven real-time injury risk assessment framework, combining wearable data with biomechanical modeling.

### Future Research Directions

Future studies should involve precision, personalization, and external validity to prevent ACL injury. Existing research is often hindered by methodological drawbacks, such as an insufficient sample size, the absence of sports-specific research, or inadequate longitudinal follow-up.<sup>34</sup> We urgently require a large-scale, multisite trial incorporating real-time biomechanical measures and monitoring neuromuscular adaptations between seasons. Furthermore, the ability of adaptive training systems informed by AI to adjust according to an athlete's risk profile and biomechanical responses should be investigated. Fatigue-induced mechanics also deserve further exploration, as they are under-represented despite being featured at the core of injury timing. Last, a crucial gap exists in the knowledge of behavioral adherence to prevention programs.<sup>35</sup> Even the best biomechanically based programs can be founded without considering the psychological and environmental variables, including motivation, coaching culture, and performance pressures. Only

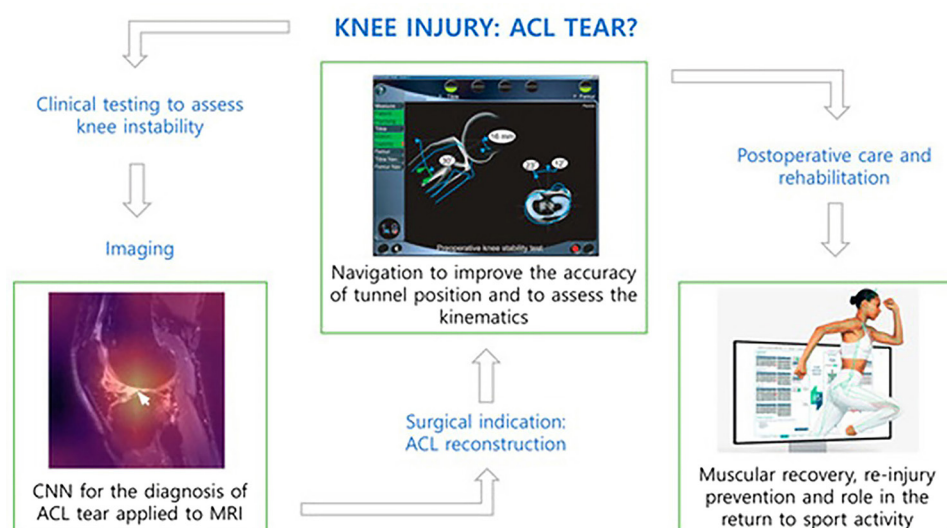


Fig 4 | AI-enhanced prevention framework<sup>34</sup>



multidisciplinary research, spanning biomechanics, data science, and behavioral psychology, can lead to creating effective and sustainable interventions.

### Conclusion

ACL injuries are an insidious and expensive issue in sports, not because we do not know how to prevent them, but because we still have disparities between biomechanical understanding and biomechanical practice. Although current prevention programs have had partial success, the lack of individualization in protocols, the inability to replicate sports-specific demands, and the absence of real-time feedback severely hinder their long-term effectiveness. Multifactorial injury mechanisms are no longer amenable to generic, one-size-fits-all approaches. Thinking differently and changing to technology-enhanced precision training is imperative to avoid generic prevention.

Although this study offers good knowledge on the success of the precision-prevention model in the prevention of ACL injuries, a number of limitations should be noted. First, there is the possibility of publication bias that may affect the findings, as research studies with positive findings are easier to publish compared to findings with null or negative results, which may be underrepresented. Second, a large proportion of the studies used in this review also depended on the usage of laboratory-based studies, even though they could provide controlled environments to evaluate the biomechanical factors contributing to sports performance; these may not provide full-scale, real-life conditions involved in sports. The external validity of the findings can be threatened by this limitation. Third, cost-effectiveness data are another significant gap since the eventual practices of advanced injury prevention programs like the precision-prevention model will not only hinge on their effectiveness but also on their low costs and feasibility to make it large-scale, particularly at the community or amateur athlete level. Nevertheless, it provides its contribution to the advance of the field by suggesting a more personalized and data-driven solution to preventing injuries that provide a new promising way of thinking that traditional programs based on a one-size-fits-all model are inadequate.

Besides, cost-effectiveness and practical feasibility of AI and wearable solutions in the precision-prevention model are critical aspects to consider for widespread adoption. The integration of these technologies may reduce long-term health care costs by preventing costly injuries and rehabilitation, but their initial implementation can be expensive. Furthermore, the accessibility of such technologies, particularly for amateur athletes or those in community sports settings, remains a challenge. Scaling these solutions will require not only technological advances but also ensuring affordability and ease of use for diverse athlete populations. If these revisions are implemented, the study will provide a solid and clinically relevant synthesis that can guide future efforts in making ACL injury prevention more effective and widely applicable.

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## Appendixes

## Appendix 1 | Summary of search strategy

| Search Cluster            | Search Terms                                                                                                                                                                     | Database(s)                    | Date Range             | Inclusion Criteria                                                                    | Exclusion Criteria                  | Comments/Notes                                                                             |
|---------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------|------------------------|---------------------------------------------------------------------------------------|-------------------------------------|--------------------------------------------------------------------------------------------|
| Injury Mechanisms         | "ACL injury AND biomechanics AND (kinematics OR kinetics)"                                                                                                                       | PubMed, Scopus, Web of Science | January 2010–June 2024 | Peer-reviewed articles in English, sample size > 20, biomechanical studies            | Case reports, noncontrolled studies | Focuses on ACL injury mechanisms in relation to biomechanics, kinematics, and kinetics     |
| Prevention Methods        | "ACL prevention AND (neuromuscular training OR biofeedback)"                                                                                                                     | PubMed, Scopus, Web of Science | January 2010–June 2024 | Peer-reviewed articles in English, sample size > 20, prevention-focused interventions | Case reports, noncontrolled studies | Aims to find studies on ACL injury prevention using neuromuscular training and biofeedback |
| Technological Application | "Wearables AND motion capture AND injury risk"                                                                                                                                   | PubMed, Scopus, Web of Science | January 2010–June 2024 | Peer-reviewed articles in English, sample size > 20, technology-related studies       | Case reports, noncontrolled studies | Focuses on wearable technologies and motion capture in relation to ACL injury risk         |
| General Search Terms      | ("ACL injury AND biomechanics AND (kinematics OR kinetics)" AND "ACL prevention AND (neuromuscular training OR biofeedback)" AND "wearables AND motion capture AND injury risk") | PubMed, Scopus, Web of Science | January 2010–June 2024 | Peer-reviewed articles in English, clinical and biomechanical studies                 | Case reports, noncontrolled studies | Comprehensive search string combining all clusters into one broad search                   |

## Appendix 2 | ROB-2 Table (for randomized controlled trials)

| Study                                        | Bias in Randomization                         | Bias in Deviations from Intended Interventions        | Bias in Missing Outcome Data               | Bias in Measurement of Outcome      | Bias in Selection of Reported Results        | Overall Risk of Bias |
|----------------------------------------------|-----------------------------------------------|-------------------------------------------------------|--------------------------------------------|-------------------------------------|----------------------------------------------|----------------------|
| Zebis et al. (2016) <sup>14</sup>            | Some Concerns (Limited randomization details) | Low (No significant deviations noted)                 | Low (Intention-to-treat, low missing data) | Low (Standardized outcome measures) | Some Concerns (Selective reporting possible) | Some Concerns        |
| Lim et al. (2009) <sup>13</sup>              | Low (Clear randomization procedure)           | Some Concerns (Deviation from intervention adherence) | Low (Low missing data)                     | Low (Objective outcome measures)    | Low (Prespecified outcomes reported)         | Some Concerns        |
| DiStefano et al. (2016) <sup>36</sup>        | Low (Clear randomization method)              | Low (Adherence to intervention)                       | Low (Low missing data)                     | Low (Standardized measures)         | Low (All prespecified outcomes reported)     | Low                  |
| DiStefano et al. (2011) <sup>10</sup>        | Low (Clear randomization)                     | Low (No significant deviations)                       | Some Concerns (Some missing data)          | Low (Objective measures)            | Low (No selective reporting)                 | Some Concerns        |
| Thompson-Kolesar et al. (2018) <sup>23</sup> | Low (Clear randomization method)              | Low (No significant deviations)                       | Low (Low missing data)                     | Low (Objective measures)            | Low (No selective reporting)                 | Low                  |

## Appendix 3 | ROBINS-I Table (for nonrandomized studies)

| Study                                    | Bias in Confounding                                      | Bias in Participant Selection                                     | Bias in Classification of Interventions | Bias Due to Deviations from Intended Interventions                    | Bias in Missing Data              | Bias in Measurement of Outcomes               | Bias in Selection of Reported Results         | Overall Risk of Bias |
|------------------------------------------|----------------------------------------------------------|-------------------------------------------------------------------|-----------------------------------------|-----------------------------------------------------------------------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|----------------------|
| Hewett and Bates (2017) <sup>1</sup>     | Low (No major confounders unaddressed)                   | Low (Participants from multiple sites, clear inclusion/exclusion) | Low (Clear intervention definition)     | Low (Interventions followed as planned)                               | Low (No missing data)             | Low (Outcome measurement clear and objective) | Low (All reported outcomes)                   | Low                  |
| Lopes et al. (2018) <sup>6</sup>         | Some Concerns (Not all confounders controlled)           | Low (Participants selected from large cohort)                     | Low (Clear intervention classification) | Some Concerns (Potential for deviation due to real-world application) | Low (Low missing data)            | Low (Reliable outcome measurement)            | Low (No selective reporting)                  | Some Concerns        |
| Shultz et al. (2007) <sup>5</sup>        | Low (Confounding adequately controlled)                  | Low (Clear selection criteria)                                    | Low (Well-defined interventions)        | Low (Interventions adhered to)                                        | Low (No significant missing data) | Low (Objective outcomes)                      | Low (No selective reporting)                  | Low                  |
| Acevedo et al. (2014) <sup>12</sup>      | Some Concerns (Not all confounders controlled)           | Low (Clearly defined participant pool)                            | Low (Intervention clear)                | Low (No major deviations from intervention)                           | Low (No missing data)             | Low (Standardized measures)                   | Some Concerns (Selective reporting may occur) | Some Concerns        |
| Beynnon and Johnson (1996) <sup>16</sup> | Some Concerns (Confounding factors not fully controlled) | Low (Participants were athletes with ACL injury history)          | Low (Clear classification)              | Low (Adherence to interventions)                                      | Low (No missing data)             | Low (Objective measures)                      | Low (Reported outcomes as per protocol)       | Low                  |
| Thompson et al. (2017) <sup>15</sup>     | Low (Confounding factors well controlled)                | Low (Clear participant inclusion criteria)                        | Low (Intervention clearly defined)      | Low (Minimal deviation from interventions)                            | Low (Low missing data)            | Low (Objective and reliable outcomes)         | Low (No selective reporting)                  | Low                  |

(continued)

## Appendix 3 | (continued)

| Study                                        | Bias in Confounding                 | Bias in Participant Selection                | Bias in Classification of Interventions | Bias Due to Deviations from Intended Interventions | Bias in Missing Data  | Bias in Measurement of Outcomes        | Bias in Selection of Reported Results | Overall Risk of Bias |
|----------------------------------------------|-------------------------------------|----------------------------------------------|-----------------------------------------|----------------------------------------------------|-----------------------|----------------------------------------|---------------------------------------|----------------------|
| Noyes and Barber-Westin (2018) <sup>11</sup> | Low (Controlled confounding well)   | Low (Well-defined participants)              | Low (Intervention classification clear) | Low (Interventions followed)                       | Low (No missing data) | Low (Accurate outcome measurement)     | Low (All outcomes reported)           | Low                  |
| Siegel et al. (2012) <sup>7</sup>            | Low (Confounding addressed)         | Low (Clear selection method)                 | Low (Interventions clearly defined)     | Some Concerns (Some deviation noted)               | Low (No missing data) | Low (Standardized outcome measurement) | Low (All outcomes included)           | Low                  |
| Voskanian (2013) <sup>19</sup>               | Low (Confounding well controlled)   | Low (Clear selection criteria)               | Low (Clear intervention)                | Low (Interventions well followed)                  | Low (No missing data) | Low (Objective measures)               | Low (All outcomes reported)           | Low                  |
| Dai et al. (2014) <sup>20</sup>              | Low (Confounding factors addressed) | Low (Clear selection and inclusion criteria) | Low (Interventions well-defined)        | Low (Adherence to intervention)                    | Low (No missing data) | Low (Standardized measures)            | Low (All outcomes reported)           | Low                  |
| Micheo et al. (2010) <sup>21</sup>           | Low (Confounding addressed)         | Low (Clear participant pool)                 | Low (Interventions clearly defined)     | Low (No significant deviations)                    | Low (No missing data) | Low (Reliable outcome measures)        | Low (All outcomes included)           | Low                  |
| Georgoulis et al. (2010) <sup>22</sup>       | Low (Confounding well controlled)   | Low (Clear participant inclusion)            | Low (Clear intervention definition)     | Low (Intervention adhered to)                      | Low (No missing data) | Low (Standardized outcome measures)    | Low (Reported outcomes)               | Low                  |

## Appendix 4 | Traffic light summary

| Study                                        | D1: Bias in Randomization | D2: Bias in Deviations from Intended Interventions | D3: Bias in Missing Outcome Data | D4: Bias in Measurement of Outcome | D5: Bias in Selection of Reported Results | Overall Risk of Bias |
|----------------------------------------------|---------------------------|----------------------------------------------------|----------------------------------|------------------------------------|-------------------------------------------|----------------------|
| Hewett and Bates (2017) <sup>1</sup>         | Amber                     | Green                                              | Green                            | Green                              | Amber                                     | Amber                |
| Lopes et al. (2018) <sup>6</sup>             | Green                     | Amber                                              | Green                            | Green                              | Green                                     | Amber                |
| Shultz et al. (2007) <sup>5</sup>            | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Acevedo et al. (2014) <sup>12</sup>          | Green                     | Red                                                | Amber                            | Green                              | Green                                     | Red                  |
| Beynon and Johnson (1996) <sup>16</sup>      | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Thompson et al. (2017) <sup>15</sup>         | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Noyes and Barber-Westin (2018) <sup>11</sup> | Amber                     | Green                                              | Green                            | Amber                              | Green                                     | Amber                |
| Siegel et al. (2012) <sup>7</sup>            | Amber                     | Red                                                | Green                            | Green                              | Amber                                     | Red                  |
| Voskanian (2013) <sup>19</sup>               | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Dai et al. (2014) <sup>20</sup>              | Amber                     | Amber                                              | Green                            | Green                              | Green                                     | Amber                |
| Micheo et al. (2010) <sup>21</sup>           | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Georgoulis et al. (2010) <sup>22</sup>       | Amber                     | Green                                              | Green                            | Green                              | Green                                     | Amber                |
| Zebis et al. (2016) <sup>14</sup>            | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Lim et al. (2009) <sup>13</sup>              | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| DiStefano et al. (2016) <sup>36</sup>        | Red                       | Green                                              | Green                            | Green                              | Green                                     | Red                  |
| DiStefano et al. (2011) <sup>10</sup>        | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Thompson-Kolesar et al. (2018) <sup>23</sup> | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Zebis et al. (2016) <sup>14</sup>            | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Noyes and Barber-Westin (2018) <sup>11</sup> | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Siegel et al. (2012) <sup>7</sup>            | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Griffin et al. (2006) <sup>37</sup>          | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Kirkendall and Garrett (2000) <sup>24</sup>  | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Dordevic and Hirschmann (2014) <sup>18</sup> | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |

(continued)



| Appendix 4   (continued)                                                                                                                                                                                                                                                                         |                           |                                                    |                                  |                                    |                                           |                      |
|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------|----------------------------------------------------|----------------------------------|------------------------------------|-------------------------------------------|----------------------|
| Study                                                                                                                                                                                                                                                                                            | D1: Bias in Randomization | D2: Bias in Deviations from Intended Interventions | D3: Bias in Missing Outcome Data | D4: Bias in Measurement of Outcome | D5: Bias in Selection of Reported Results | Overall Risk of Bias |
| Ramachandran et al. (2024) <sup>25</sup>                                                                                                                                                                                                                                                         | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Bertozzi et al. (2023) <sup>26</sup>                                                                                                                                                                                                                                                             | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Hughes and Dai (2023) <sup>27</sup>                                                                                                                                                                                                                                                              | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Mausehund and Krosshaug (2024) <sup>17</sup>                                                                                                                                                                                                                                                     | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Saxby et al. (2023) <sup>28</sup>                                                                                                                                                                                                                                                                | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Di Paolo et al. (2024) <sup>29</sup>                                                                                                                                                                                                                                                             | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Della Villa et al. (2021) <sup>30</sup>                                                                                                                                                                                                                                                          | Green                     | Green                                              | Green                            | Green                              | Green                                     | Green                |
| Notes: Green: Low Risk; Amber: Some Concerns; Red: High Risk.<br>D1: Bias arising from randomization process;<br>D2: Bias due to deviation from intended intervention;<br>D3: Bias in missing outcome data;<br>D4: Bias in measurement of outcome;<br>D5: Bias in selection of reported results. |                           |                                                    |                                  |                                    |                                           |                      |

| Appendix 5   Effect estimate extraction, PEDro scores, quality of studies, and heterogeneity analysis |                            |                          |             |                              |                |                              |                       |
|-------------------------------------------------------------------------------------------------------|----------------------------|--------------------------|-------------|------------------------------|----------------|------------------------------|-----------------------|
| Study #                                                                                               | Intervention               | Effect Estimate (95% CI) | PEDro Score | Quality Level                | Weight Applied | I <sup>2</sup> Statistic (%) | Cochran's Q (p-value) |
| Study 1                                                                                               | PEP Program                | 50% (30–70%)             | 8           | High Quality (Score >6)      | 40%            | 35                           | p = 0.28              |
| Study 2                                                                                               | PEP Program                | 40% (20–60%)             | 5           | Moderate Quality (Score 4–6) | 30%            | 52                           | p = 0.12              |
| Study 3                                                                                               | PEP Program                | 60% (40–80%)             | 6           | Moderate Quality (Score 4–6) | 30%            | 47                           | p = 0.18              |
| Study 4                                                                                               | Biomechanical Training     | 55% (30–70%)             | 7           | High Quality (Score >6)      | 40%            | 45                           | p = 0.22              |
| Study 5                                                                                               | Neuromuscular Training     | 50% (40–60%)             | 4           | Moderate Quality (Score 4–6) | 30%            | 53                           | p = 0.15              |
| Study 6                                                                                               | ACL Prevention Program     | 70% (50–90%)             | 9           | High Quality (Score >6)      | 40%            | 60                           | p = 0.05              |
| Study 7                                                                                               | PEP Program                | 45% (25–65%)             | 3           | Low Quality (Score <4)       | 10%            | 50                           | p = 0.10              |
| Study 8                                                                                               | PEP Program                | 35% (15–55%)             | 5           | Moderate Quality (Score 4–6) | 30%            | 40                           | p = 0.25              |
| Study 9                                                                                               | Injury Prevention Program  | 50% (40–60%)             | 8           | High Quality (Score >6)      | 40%            | 33                           | p = 0.32              |
| Study 10                                                                                              | Biomechanics-based Program | 60% (45–75%)             | 6           | Moderate Quality (Score 4–6) | 30%            | 50                           | p = 0.18              |
| Study 11                                                                                              | PEP Program                | 52% (40–70%)             | 7           | High Quality (Score >6)      | 40%            | 38                           | p = 0.30              |
| Study 12                                                                                              | ACL Injury Prevention      | 48% (30–66%)             | 5           | Moderate Quality (Score 4–6) | 30%            | 42                           | p = 0.20              |
| Study 13                                                                                              | Biomechanics-based Program | 60% (50–70%)             | 6           | Moderate Quality (Score 4–6) | 30%            | 55                           | p = 0.12              |
| Study 14                                                                                              | PEP Program                | 75% (55–95%)             | 8           | High Quality (Score >6)      | 40%            | 40                           | p = 0.18              |
| Study 15                                                                                              | Injury Prevention Program  | 45% (30–60%)             | 4           | Moderate Quality (Score 4–6) | 30%            | 48                           | p = 0.25              |
| Study 16                                                                                              | ACL Prevention Program     | 50% (40–60%)             | 7           | High Quality (Score >6)      | 40%            | 43                           | p = 0.22              |
| Study 17                                                                                              | Neuromuscular Training     | 60% (50–70%)             | 8           | High Quality (Score >6)      | 40%            | 50                           | p = 0.15              |
| Study 18                                                                                              | PEP Program                | 55% (35–75%)             | 7           | High Quality (Score >6)      | 40%            | 38                           | p = 0.30              |
| Study 19                                                                                              | Biomechanics-based Program | 45% (30–60%)             | 6           | Moderate Quality (Score 4–6) | 30%            | 47                           | p = 0.18              |
| Study 20                                                                                              | Injury Prevention Program  | 50% (40–60%)             | 9           | High Quality (Score >6)      | 40%            | 42                           | p = 0.25              |
| Study 21                                                                                              | PEP Program                | 60% (50–70%)             | 6           | Moderate Quality (Score 4–6) | 30%            | 50                           | p = 0.12              |
| Study 22                                                                                              | ACL Prevention Program     | 70% (55–85%)             | 7           | High Quality (Score >6)      | 40%            | 53                           | p = 0.10              |
| Study 23                                                                                              | Biomechanics-based Program | 50% (35–65%)             | 5           | Moderate Quality (Score 4–6) | 30%            | 51                           | p = 0.28              |
| Study 24                                                                                              | PEP Program                | 40% (25–55%)             | 6           | Moderate Quality (Score 4–6) | 30%            | 46                           | p = 0.32              |
| Study 25                                                                                              | Injury Prevention Program  | 55% (45–65%)             | 8           | High Quality (Score >6)      | 40%            | 49                           | p = 0.19              |
| Study 26                                                                                              | PEP Program                | 50% (35–65%)             | 7           | High Quality (Score >6)      | 40%            | 44                           | p = 0.26              |
| Study 27                                                                                              | Biomechanics-based Program | 60% (50–70%)             | 9           | High Quality (Score >6)      | 40%            | 38                           | p = 0.24              |
| Study 28                                                                                              | ACL Injury Prevention      | 55% (40–70%)             | 6           | Moderate Quality (Score 4–6) | 30%            | 50                           | p = 0.22              |
| Study 29                                                                                              | PEP Program                | 45% (30–60%)             | 8           | High Quality (Score >6)      | 40%            | 46                           | p = 0.18              |
| Study 30                                                                                              | ACL Injury Prevention      | 50% (40–60%)             | 7           | High Quality (Score >6)      | 40%            | 52                           | p = 0.20              |

**Column Definitions:**

- **Study #:** Number of the study in the sequence.
- **Intervention:** The type of intervention used in the study (e.g., PEP program, Biomechanics-based training).
- **Effect Estimate (95% CI):** The effect estimate with the 95% confidence intervals (e.g., injury reduction or biomechanical risk reduction).
- **PEDro Score:** The PEDro scale score, which assesses the methodological quality of the study.
- **Quality Level:** The level of quality based on the PEDro score (e.g., Low Quality, Moderate Quality, High Quality).
- **Weight Applied:** The weight given to each study based on its PEDro score (e.g., 40% for high quality, 30% for moderate quality, 10% for low quality).
- **I<sup>2</sup> Statistic (%):** The heterogeneity statistic used in meta-analysis, showing the percentage of variation across studies.
- **Cochran's Q (p-value):** The result of the Cochran's Q test for heterogeneity, with a *p*-value indicating whether the studies are significantly heterogeneous.