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Anterior Cruciate Ligament Injuries in Competitive Athletes

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Abstract. Anterior cruciate ligament injuries are one of the most common and most troublesome injuries in competitive sports. They are often seen in sports that involve changes of direction, cutting, pivoting and rapid deceleration. They often occur in many sports and can be associated with high and low-contact injuries. Despite large amounts of research, similar injury patterns and recurrence rates have not changed, suggesting that current prevention interventions are ineffective. This paper investigates anterior cruciate ligament injuries using a framework that incorporates both biomechanical mechanisms, along with intrinsic and extrinsic risk factors and current prevention strategies. Most anterior cruciate ligament injuries appear to be the result of non-contact mechanisms of injury. A very small proportion of injuries are a result of contact. They should not be viewed as the result of isolated joint dysfunction, but instead, the result of poor motor coordination. In addition to biomechanical factors, the cognitive demand and mental preparedness of the athlete appear to have a significant impact on injury risk, especially in competitive situations, and this influence is often reflected in the psychology of the athlete and self-perceptions.

Keywords: Anterior cruciate ligament (ACL), injury prevention, neuromuscular training, non-contact injury, athletic performance

1. Introduction

Anterior Cruciate Ligament injuries are one of the most common and most clinically relevant injuries seen in competitive sports. They are often seen in sports that involve changes of direction, cutting, pivoting and rapid deceleration [1]. This results in a lot of mechanical stress on the knee joint. This can lead to injury and damage to the knees and result in damage to the ligaments. In addition to the primary trauma, anterior cruciate ligament injuries can have prolonged effects that extend beyond the initial injury, which can affect athletes' mental health. Athletes often experience a prolonged rehabilitation process, which can lead to a loss of confidence in their ability to compete and make them doubt their ability to return to their previous level of performance. A successful return to sport after anterior cruciate ligament injury and reconstruction, with structured rehabilitation, is not guaranteed and is often followed by an increased risk of further injury [2,3]. This has led to a redefinition of the term 'injury prevention'. Injury prevention has traditionally focused on the avoidance of initial injuries, the aim being to prevent athletes from getting injured. When it comes to anterior cruciate ligament injury, this is too narrow a focus. Many athletes

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continue to present with asymmetrical loading patterns and neuromuscular deficits, as well as being psychologically hesitant, despite being medically cleared to return to sport [4,5]. As such, prevention needs to be viewed as a continuum that encompasses both primary and secondary prevention strategies throughout an athlete's career.

2. Mechanisms of non-contact ACL injury in competitive sports

2.1. Core biomechanical injury mechanisms

The majority of ACL injuries appear to be sustained via a non-contact mechanism rather than during direct contact [1,2]. These injuries typically happen when there is sudden deceleration, landing after a jump, or changes in movement direction. They can also happen during acceleration, changing direction, or when running sideways, as mechanical stress is placed on the knee joint during these activities. There are several biomechanical patterns that have been identified as contributing to injury risk during activities such as these. These include dynamic knee valgus, anterior tibial translation, and excessive rotational forces through the knee joint [2]. If all of these factors happen simultaneously, it places a greater load on the anterior cruciate ligament than it is capable of withstanding, thus compromising joint stability. Dynamic knee valgus has garnered considerable attention within the literature as it relates to ACL injury, as this position reflects the combined activity of hip adduction, internal rotation, and medial knee collapse during movement [2]. It may be more accurate, however, to suggest that the problem with injury is not that this single factor is not being controlled sufficiently, but rather ACL injury is an injury that is better explained by a failure of coordinated movement at all the joints within the kinetic chain [2,6]. For example, poor trunk control, limited hip stability, failure to produce adequate hamstring activation during early stages of the movement, and poor landing mechanics can all increase the load through the knee [6]. These factors rarely, if ever, happen in isolation. Instead, they combine and interact with one another when performing high-demand tasks, creating a situation where the load through the knee is greater than the structures within the joint can withstand. Additionally, recent research has highlighted the impact that cognitive demand has on movement quality in athletes. When an athlete is required to react to unpredictable stimuli and make fast decisions, the quality of their biomechanical control can be compromised, leading to injury. Therefore, ACL injury risk is not only biomechanical in nature, but also context-dependent. The physical and cognitive demands placed on the athlete can increase or decrease the risk of injury.

2.2. Cognitive-motor interaction and task-dependent injury risk

Two recent systematic reviews have extended this mechanism by showing that movement quality and biomechanical control are dose-related to cognitive demand [6]. Systematic reviews have shown that when athletes are presented with unpredictable visual stimuli, tactical game demands, divided attention requirements or rapid decisions, they display similar consistent biomechanical markers of elevated ACL injury risk.

This is clinically important as it is rare in tactical sports for real-match scenarios to involve pre-planned, controlled laboratory movements performed in a closed kinematic chain. Instead, athletes must rapidly respond to opponents, teammates, ball trajectories and tactical pressure with an extremely limited time frame. A pattern that is low risk in a closed, pre-planned laboratory movement pattern may be highly uncontrolled and high risk in an open, unpredictable competitive task. For this reason, we must interpret ACL injury mechanisms as task-specific and context-

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dependent rather than purely anatomically driven. We must examine not only the static alignment of the knee and mechanics of controlled movements, but also how that athlete is able to maintain biomechanical control under performance and competitive cognitive demands [6].

3. Intrinsic and extrinsic risk factors for ACL injury

3.1. Intrinsic risk factors

Modifiable intrinsic risk factors have received a considerable amount of attention in ACL injury research, particularly in attempts to explain well-characterized sex differences in injury rates. Female athletes sustain a disproportionately high incidence of ACL injury in the majority of cutting and pivoting team sports [2]. Researchers have proposed a multifactorial explanatory model for sex differences in ACL injury that includes: anatomic differences, hormonal fluctuations, generalized joint laxity, and sex-specific differences in patterns of neuromuscular control [2]. Anatomically, a wider pelvic width, altered lower extremity alignment, or greater ligamentous laxity may result in a biomeomechanical profile that predisposes to increased knee joint loading during dynamic movement. Further, hormonal fluctuations at various points throughout the menstrual cycle have been proposed to modify ligament tensile properties and neuromuscular performance. However, these hormonal associations have not been consistently and reproducibly demonstrated across the peer-reviewed literature [2].

It is also essential to avoid viewing intrinsic risk factors as biological destiny. This view of intrinsic risk is deterministic and ignores the compelling evidence that most modifiable intrinsic deficits can be identified and improved through careful screening and neuromuscular training interventions. For example, neuromuscular strength imbalances, delayed hamstring activation, asymmetrical lower extremity loading, and poor landing force absorption can all be objectively identified through standardized screening and can be improved with targeted exercise programs [2,4]. Therefore, while fixed anatomical characteristics are difficult to change, an athlete's ability to dynamically stabilize the knee joint during high-demand movements can be greatly improved with targeted training. This is clinically significant because viewing intrinsic risk as fixed biological destiny ignores the interaction between biological characteristics and movement patterns and structured training.

A prior history of ACL injury is the most significant modifiable intrinsic risk factor, particularly for competitive athletes who sustain a second ACL injury while returning to sport after reconstruction. A history of ACL injury is not simply a marker of previous trauma, but is often associated with persistent residual neuromuscular and sensorimotor impairments that continue to influence movement mechanics and increase the risk of reinjury [4]. Research aimed at secondary ACL injury prevention has documented persistent muscular weakness, bilateral neuromuscular asymmetry, movement confidence, and sensorimotor control after return to competitive sport [4]. Even when standardized clinical rehabilitation milestones are met, the reconstructed knee rarely returns to the same biomechanical function as the uninjured contralateral lower extremity. This, in part, explains why the risk of a second ACL injury remains increased after the formal end of rehabilitation.

3.2. Psychological intrinsic risk factors

Psychological readiness is an underappreciated but important intrinsic risk factor for ACL injury and reinjury. A systematic review and meta-analysis of psychological readiness to return to sport after

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anterior cruciate ligament injury: The Anterior Cruciate Ligament Return to Sport after Injury Scale (ACL-RSI) scores revealed that psychological recovery is a prolonged, individualized process that influences return-to-sport outcomes and long-term athletic participation [5]. Movement confidence, fear of reinjury, and the athlete's perceived physical and psychological readiness state directly influence how the athlete loads the previously injured limb, how aggressive the cutting/landing mechanics are, and how well the athlete can move 'naturally' in the competitive environment and in an unpredictable manner. Thus, assessment of the athlete's risk state cannot be limited to an evaluation of anatomical and neuromuscular function; a holistic risk assessment must include the athlete's state of mind because a state of full physical recovery without a corresponding state of psychological readiness leaves the athlete continually vulnerable to overuse and contact reinjury [5].

3.3. Extrinsic risk factors

Although intrinsic risk factors have traditionally driven ACL research, extrinsic risk factors have a critical and underappreciated influence on injury pathogenesis and remain underinvestigated in some athletic populations. A recent systematic review of adolescents 14-18 years of age demonstrates the strong predictive value of sport exposure volume and environmental playing conditions, athlete equipment, and contextual competitive factors in primary non-contact ACL injury [3]. Sport type is a significant extrinsic variable: sports that demand repeated cutting/pivoting, rapid acceleration and jump-landing generate a greater ACL loading exposure than sports with minimal change in direction or vertical loading, explaining the relatively high primary injury rates in soccer, basketball, handball and other field/court sports. Competition level also independently modulates injury risk. Elites have a faster movement velocity, greater physical contact, more aggressive cutting/landing, and a closer weekly training and match load. These factors serve to amplify the mechanical loading demand while reducing the athlete's margin of error in movement control. An athlete performing a cutting movement pattern in elite competition experiences a different mechanical loading profile than an athlete performing the same movement in a recreational setting; that is, the same technical movement pattern will have different injury risk depending on the competitive context [3]. The environmental variables deserve greater research attention than currently allocated. Playing surface properties, shoe-surface interaction, and weather conditions all influence lower extremity loading mechanics. For example, too much surface traction interaction may limit the range of free foot rotation and increase torsional loading on the knee joint; some playing surfaces may interfere with deceleration mechanics, particularly in a fatigued athlete [3]. These extrinsic factors are more difficult to isolate experimentally than anatomical variables but have high clinical relevance in a sport context.

3.4. Workload, fatigue and cognitive-physical interaction

Training and competition workload, cumulative exposure volume and exercise-induced fatigue are particularly potent extrinsic and intermediary risk factors. As training or match load goes up, players have consistently been shown to display poor landing mechanics, are slower to react and possess reduced neuromuscular control. More critically, fatigue is not a simple physical state; it multiplies the negative effects of heightened cognitive demand on movement. At the end of competitive matches, players must perform under both elevated physiological fatigue and diminished attentional efficiency, creating a highly hazardous environment for aberrant movement and ACL injury [3]. For this reason, extrinsic risk factors should not be viewed as weak contextual variables that can be easily brushed aside, but instead require careful, specific monitoring using appropriate measurement

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tools – particularly in the adolescent and elite competitive populations where rapid physical growth, training load and match exposure interact in novel, synergistic ways [3].

4. Evidence-based ACL injury prevention strategies

Because the multifactorial, interacting causes of ACL injury exist in combination, the optimal prevention strategies are also multicomponent and integrated rather than single-exercise or isolated screening programmes. There is strong contemporary sports medicine evidence to support the use of prevention programmes that combine elements of structured neuromuscular training, strength development, plyometric exercise and movement retraining [1, 4,7-10]. The primary aim of these programmes should be not only to reduce the incidence of primary and secondary injury, but also to improve dynamic movement control, intermuscular coordination and efficient movement patterns during sport-specific activities.

4.1. Neuromuscular and strength training

Neuromuscular training is currently the most widely recommended component of prevention programmes, and is designed to improve dynamic motor control, joint stability and coordinated movement patterns under high-velocity, unstable conditions [9]. A controlled clinical trial in high school athletes showed that, in both boys and girls, structured neuromuscular training can induce meaningful improvements in a range of physical performance measures [9]. Although improved performance does not directly translate to a reduction in injury risk, these findings provide strong confirmation that meaningful modifications can be made to the physical attributes associated with safe movement mechanics using appropriate training interventions. There is also strong meta-analytic support for the use of neuromuscular training to reduce knee injury risk in female team sport athletes [10].

Targeted strength development is equally important, particularly for the posterior muscular chain. The hamstring and hip musculature provide important dynamic knee stabilisation, and low posterior chain activation and strength contribute to a relative overdependence of the knee joint on its passive ligamentous structures, such as the ACL [2]. Targeted strength development, particularly for the posterior muscular chain, is equally critical. The hamstring and hip musculature provide essential dynamic knee stabilization, and insufficient posterior chain activation and strength leave the knee joint overly reliant on passive ligamentous structures such as the ACL [2].

4.2. Plyometric and landing control training

Plyometric and structured landing-control training play a central role in ACL prevention, because these interventions teach athletes to effectively manage impact forces, reduce uncontrolled frontal-plane knee motion and maintain neutral lower extremity alignment during the most commonly occurring high-risk scenario for ACL injury – the jump-landing task [1,10]. When delivered under qualified supervision, these interventions will improve an athlete's ability to safely handle the high-impact loading conditions that precede most non-contact ACL injuries.

4.3. Neurocognitive and dual-task training

New research is beginning to support the preventive potential of neurocognitive training and sport-specific dual-task integration (which requires movement in combination with cognitive demand), such that there is growing evidence from narrative and systematic reviews that adding reaction time

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demands, attentional challenges, and real-time decisions to physical training bridges the gap between what we can safely do with 'mock' prevention demands and what the sport specifically requires of the athlete [6,8]. This is a huge step forward in prevention programming because it allows trainees to demonstrate safe movement mechanics under cognitive demand, not just in the controlled rehearsal.

4.4. Secondary prevention post-ACL reconstruction

Secondary prevention is particularly unique and important after ACL reconstruction. Wong et al. suggest that many current rehabilitation programs are missing a critical middle phase: the process of transitioning from a formal rehabilitation completion to a true competitive return-to-sport readiness [4]. A medical clearance to return to sport does not necessarily mean that the neuromuscular, physical, and psychological capacities necessary for a patient to play any sport without restrictions have been restored. Thus, ACL injury prevention must be viewed as a longitudinal, extended process that can and should be performed both pre-injury (primary prevention), during the post-surgical rehabilitation, and while returning to competitive sport. Checking a box on a pre-season screening checklist and performing a single block of training lasting a couple of hours is insufficient to maintain risk for many seasons.

5. Limitations of current ACL prevention research

Despite the current hype around ACL prevention programs, the research literature upon which it is based contains several inconsistencies and conflicting findings that make ACL prevention programs amenable to universal implementation. One major limitation is that not all prevention programs result in measurable changes in the specific biomechanical risk factors. A recent systematic review and meta-analysis found that typical injury prevention programs did not significantly change most lower extremity kinematic and kinetic variables in female team field and court sport athletes [7]. This finding provides a critical blow to a common applied sport science assumption that decreased injury rates must result from 'fixing' specific biomechanical faults.

If prevention programs lower injury incidence but do not typically alter commonly reported biomechanical risk variables, the causal protective pathway is probably more complicated than the simplistic "correct the bad mechanics to prevent injury" model. More general improvements in movement coordination, attentional focus, athletic preparedness, or movement adaptability may induce protective effects, even if isolated joint-level biomechanical metrics remain relatively similar [6-8]. This does not undermine current prevention programs, but does necessitate more careful interpretation and an end to the tendency towards using mechanical reductionism as a crutch.

A second major limitation is the great heterogeneity across prevention studies. There is considerable variability across studies in the type of sport, age group, intervention duration, intervention content, athlete adherence, and outcome measure [1,7,10]. Some programs are delivered in short blocks during pre-season, others are incorporated into regular training over multiple months; some studies measure biomechanical outcomes, others measure injury incidence, and others measure performance outcomes. Intervention adherence is variable yet strongly predictive of intervention success: a theoretically sound program delivered with poor consistency will appear to be ineffective, while a simple program delivered with high reliability will still show significant risk reduction. This variability limits direct comparison between studies and weakens the strength of a universal conclusion.

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6. Future directions and applied practical recommendations

Recommendations taken collectively, the available literature suggests that generalized multicomponent prevention programs serve as an important starting point, but are inadequate as a single, general solution for all athletic populations. Standardized neuromuscular and plyometric programs provide a sensible, concrete starting point for a team-based intervention, particularly for youth and scholastic sports [9,10]. In contrast, individualized, risk-stratified prevention models provide a more accurate, specific approach for elite competitive athletes [4,5].

An integrated, modern screening framework should include biomechanical, neuromuscular, cognitive, and even psychological variables rather than simply focusing on observable mechanics of a movement during a controlled task [5,8]. Screenings that focus on static knee alignment and pre-planned landings may miss athletes who perform well in controlled settings but display high-risk mechanics when cognitively challenged or anxious about return to sport. Three evidence-based practical recommendations follow for applied athletic and clinical settings. First, program adherence should be a primary outcome variable, not a secondary consideration – even well-designed programs cannot reduce injury risk without consistent, longitudinal implementation [1,4]. Second, athlete education should be improved to position injury prevention as an important component of performance optimization, not a superficial injury-avoidance strategy. Third, prevention programming should be sport-specific and longitudinally continuous, incorporating primary prevention, objective return-to-sport decision-making, and secondary reinjury prevention into a cohesive, integrated model [4,5]. This latter model is probably closer to the truth of the dynamic, multifactorial nature of ACL injury risk in competitive athletics.

7. Conclusion

Recurrent ankle sprains are a complex clinical condition involving persistent changes to ankle biomechanics and neuromuscular control rather than being simply recurrent isolated injuries. The evidence in this paper indicates that targeted rehabilitation interventions can effectively improve key aspects of ankle function. Joint mobilization has been shown to heighten the dorsiflexion range of motion and improve landing mechanics, so as to restore better joint positioning in dynamic tasks. Besides, balance and proprioceptive training result in enhanced postural control and sensorimotor integration. Findings show significant improvements in functional assessments including the SEBT and FAAM, and a lower likelihood of recurrent sprains. Strength training of the peroneal and calf musculature helps joint stability by increasing muscle responsiveness and control during weight-bearing movements. Importantly, the integration of these rehabilitation components appears to produce greater improvements than isolated interventions, including increased movement symmetry, reduced compensatory strategies at the knee and hip, and improved performance in functional tasks. These findings propose that rehabilitation should be looked at as a complete, progressive process with a step-by-step move from simple to more complex tasks, instead of a collection of isolated interventions. It's vital to deal with both mechanical deficits, for example, restricted ankle dorsiflexion, and neuromuscular dysfunction, such as proprioceptive dysfunction, to bring back normal ankle biomechanics and cut the re-injury risk. The study shows the value of applying individualized, evidence-based rehabilitation plans in clinical and sports settings. Through the combination of different training elements and a focus on long - term functional effects, rehabilitation programs can lower the recurrence rate and help people involved in regular physical activity hold on to their athletic performance and joint health.

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