Anterior cruciate ligament injury prevention

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Abstract: Anterior cruciate ligament injuries are a prominent issue in the field of sports medicine, especially for the female athlete. Extensive research has been performed that acknowledges the disparity in anterior cruciate ligament injury rates between male and female athletes and the high prevalence of risk factors specific to females. The underlying causes of anterior cruciate ligament injuries are widespread and are important to consider when approaching injury prevention. For example, prevention techniques aim to correct neuromuscular imbalances and improve biomechanical deficits, which are some of the most significant risk factors leading to these injuries. While there is a lack of opportunity for intervention related to anatomical and hormonal risks, awareness of their influence on injury mechanisms remains an important factor in clinical decision-making. In pursuit of addressing the risks of this injury, several prevention programs have been established that have been shown to successfully reduce anterior cruciate ligament injury rates when properly executed. The most effective programs include early intervention with continuous training and are multicomponent programs including various targeted exercises to modify associated risk factors. Unfortunately, despite the development of these readily available programs, anterior cruciate ligament injury rates remain high due to insufficient implementation of these methods. Recognizing the efficacy and feasibility of utilizing prevention strategies and continuing to develop effective techniques remain of utmost importance to reduce the incidence of this substantial injury among athletes.

Keywords: Anterior cruciate ligament (ACL); injury prevention; sports injury; female athlete

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Introduction

The anterior cruciate ligament (ACL) functions as a key stabilizer for the knee and is critical for athletes participating in a variety of sports, particularly multidirectional sports with frequent cutting, pivoting, and jump-landing activities. ACL ruptures are considered debilitating knee injuries and are among the injuries that receive the most attention in sports medicine. In general, ACL ruptures account for over 50% of all knee injuries and most commonly require surgical treatment, resulting in high healthcare costs and great impact on the individual both physically and mentally (1). The severity of this injury is compounded by long recovery and rehabilitation post-reconstruction, time loss from participation in sport, compromised ability to return to previous level of play, and can even impact an athlete's decision to continue to play after recovering from surgery. In a 2019 study assessing athletes at 2-year following ACL surgery, as many as 62% of female soccer athletes quit playing after sustaining an ACL injury due to lack of trust in the reconstructed knee or fear of new injury (2). Long-term consequences also exist for individuals that experience an ACL rupture, including an up to 80% possibility of developing arthritis in the affected knee within 15 years (3). There is also a high risk of sustaining a second ACL injury to the reconstructed knee and injury to the contralateral knee, especially in athletes that return to participation in sport (2,4). Compared to their male counterparts, female athletes consistently suffer ACL injuries at a significantly higher rate, with some reports of incidence rates as high as 8 times greater, and have a greater risk of further ACL injury post-reconstruction (1-4). Noncontact mechanisms of ACL injury and sex differences in various risk factors have been extensively researched to better understand disparities in injury rates. Comprehension of the risks involved and awareness of the substantiality of ACL injuries ultimately purposes to assist in developing effective intervention methods to reduce risk and ACL injury rates in highly susceptible athletes.

Epidemiology

Recognizing the epidemiology of ACL injuries in athletes is an important aspect of establishing viable injury prevention programs, particularly noting the difference in injury rates between males and females, and the variations in rates and mechanisms by sport. In an updated prospective 9-year study of collegiate ACL injury rates across 15 sports in the National Collegiate Athletic Association (NCAA), it was reported that among sex-comparable sports including basketball, lacrosse, and soccer, females sustained significantly higher rates of ACL injury compared to males (5). Within each sport, the injury rate per 1,000 athlete-exposures (AEs) in females compared to males was higher in all cases (0.22 versus 0.08 in basketball, 0.23 versus 0.13 in lacrosse, and 0.10 versus 0.04 in soccer). These general patterns in rate differences remained consistent throughout the course of the study and only a few sports saw a decrease in ACL injury rates, despite the development of prevention programs during the time that the study took place. Importantly, when comparing the data in this study to the data in a previous study performed by the same authors between years 1988–2004, there was a significant reduction in overall ACL injury rate, with the highest reduction observed in men's soccer (56% decrease). Notably in this study, 60% of ACL injuries among females occurred through noncontact mechanisms, while male athletes sustained more ACL injuries due to contact mechanisms (59%).

Montalvo *et al.* recently performed a systematic review and meta-analysis of 36 articles to determine the ACL injury risk in sport, specifically attempting to look at ACL injury incidence by sex and sport classification (6). Sports were categorized into collision, contact, limited-contact, noncontact, and fixed-object, high-impact rotational landing (HIRL). In each sport classification, females had a higher incidence rate of ACL injury than males, with contact and fixed-object HIRL reaching statistical significance. This observation provides evidence regarding the role of sport type in ACL injury and relevant information on the sex differences in injury rate that exists when comparing more generally by sport type. In a 5-year, multisport epidemiology study representing ACL injuries in high school sports nationally, a total of 617 ACL injuries were reported, which accounted for 20.5% of knee injuries and 3.0% all injuries, for an overall rate of 6.5 ACL injuries per 100,000 AEs (1). Overall, males and females had similar ACL injury rates, but among sex comparable sports (basketball, soccer, and baseball/softball), females had a significantly higher incidence rate compared to males at 8.9 and 2.6, respectively. Generally speaking, variations in ACL injury rates and mechanisms by sex and sport were found in this study and the recognition of these differences is crucial in implementing the most effective intervention techniques through targeted prevention programs.

When discussing ACL injury prevention, it is also important to recognize the epidemiology of ACL injuries across all levels of play. At the elite level of play, for example, ACL tears continue to occur at a higher rate in females than in male athletes. In a 5-season prospective study performed among professional soccer players in Spain, despite less overall females included in the study, ACL ruptures were 5 times more common among females, accounting for over 40% of time lost from participation (7). Additionally, females had a 21% greater number of total days lost and overall, twice the injury burden compared to males. At a professional level, these consequences of ACL injury greatly impact not only the individual, but the club and their team as well, indicating the need for greater emphasis to be placed on the importance of the prevention efforts.

ACL rupture is also an impactful injury in youth soccer athletes and athletes in their late adolescence, where females similarly remain at greater risk compared to males (8). Suffering from a significant injury such as this can lead to a decrease in athletic participation and physical activity, which are considered beneficial for many reasons, especially in younger populations (1). The high level of ACL injury risk and its potential consequences in adolescent athletes is comparable to elite athletes and those in between, indicating the importance of injury prevention programs at every level of competition.

Etiology of ACL injury

Better understanding of the potential underlying causes of

ACL injury provides an important baseline in establishing effective prevention strategies that minimize these risk factors. In particular, studying noncontact mechanisms of injury provides clinically relevant information on modifiable risk factors, which are the key aspect of injury prevention. The most common noncontact mechanisms that lead to ACL rupture include rapid change of direction during deceleration, stopping abruptly, and landing from a jump (8,9). Reasons for the high prevalence of noncontact ACL injuries as well as the predominance in females are multifactorial, and extensive research has been performed to better comprehend the risk factors involved. These risks can be characterized as nonmodifiable or modifiable, and both are essential in understanding the mechanics that lead to an ACL tear.

Nonmodifiable risk factors

Beginning with anatomical considerations, multiple studies have analyzed sex and age differences as they relate to ACL injury risk, but evidence in this area generally remains inconclusive. Proposed anatomical risk factors for ACL rupture include smaller ACL size, narrow intercondylar notch, increased generalized ligamentous laxity, lower extremity malalignment, and greater posterior-inferior directed tibial slope (3,10,11). Hormonal influences have also been evaluated as potential risk factors, with observations by several researchers suggesting that greater ACL injury risk occurs when hormone levels are most varied, and the greatest divergence in incidence rate between males and females occurs at the start of puberty when sex hormonal profiles are most different (12,13). With that said, estrogen and progesterone have been linked to ACL injury risk in relation to overall influences of sex hormones on ACL structure and neuromuscular function. Numerous studies have reported a greater predisposition to injury in females during the preovulatory phase of the menstrual cycle, which some researchers have associated with estrogen fluctuations (12,14,15). It has also been shown that the use of oral contraceptives in premenopausal women, which generally functions to inhibit the fluctuations of estrogen, reduces ACL injury risk by increasing stability of the ACL and neuromuscular control relative to non-oral contraceptive users (13,15). The overall effects of estrogen and its role in ACL injuries in females remain somewhat controversial and appear to depend on age, hormonal status, and level of activity. Few studies have analyzed the relationship between testosterone and ACL injury, but it has been generally reported to play a strengthening role in the ACL (16). Stijak *et al.* studied the effects of hormone levels in female athletes in Serbia and found significantly lower levels of testosterone in ACL-injured athletes compared to uninjured athletes (16). Increased incidence of ACL tears has also been observed in athletes with higher levels of relaxin compared to knee-healthy individuals, indicating potential collagenolytic properties of this hormone (17). Interestingly, relaxin receptors have been identified on the ACL of females, but not in males, and estrogen and progesterone receptors have also been located on the ACL of humans, further supporting the influence of sex hormones on ACL injury (3,15,17). Additional nonmodifiable risk factors to consider include younger age under 20 years old, female sex, poor weather conditions for outdoor sports, genetic predisposition, and previous history of knee injury. Screening for these risks can improve clinical decision-making and awareness of the predisposed risks an individual may possess is meaningful information, but the lack of opportunity for intervention in this area has led researchers to focus on modifiable risk factors when developing prevention programs.

Modifiable risk factors

The most effective intervention techniques include components that address improving neuromuscular and biomechanical deficits related to noncontact ACL injuries. Hewett *et al.* observed that decreased neuromuscular control and increased valgus loading are predictors of increased ACL injury risk in a prospective study on female athletes (18). To determine this, their research team prescreened biomechanical measures and found significant differences in knee posture and loading between athletes that went on to sustain an ACL injury and those that did not. More specifically, ACL-injured athletes showed increased knee abduction loads, higher ground reaction force, and greater dynamic valgus compared to uninjured athletes during landing, cutting, and decelerating maneuvers. Dynamic valgus is described as knee valgus and low flexion angle with the center of gravity behind the knee, which is a position involved in the most common noncontact ACL injury mechanism in female athletes (10). Additional risk factors that have been observed in female athletes during landing, cutting, and pivoting include weak knee flexors, less flexion in the knee and hip, greater internal rotation of hip, and increased external rotation of the tibia, which can be altered by proper neuromuscular training (10,11). Similar studies have analyzed the role of muscle activation, frequently finding higher injury risk in athletes with predominant quadriceps activity relative to the hamstrings (18). The hamstrings are considered protective flexors and act as an important knee stabilizer contrary to the quadriceps, which place strain on the ACL at low flexion angles (10,19). Proper co-activation and coordination between these complementary muscles is a critical aspect of dynamic knee stabilization.

Prevention techniques focused on improving neuromuscular control can correct hamstring activity deficits, which decreases the loads placed on the ACL from the quadriceps and ultimately reduces the risk of rupture (15). Further risk for ACL injury is involved in other muscular imbalances, as observed by Khayambashi *et al.* in athletes from competitive clubs in Iran (20). This study prescreened athletes of various sports prior to the start of their season and found significantly lower baseline hip strength measures, particularly external rotation and abduction, in the athletes that suffered noncontact ACL injuries during the season compared to the uninjured athletes. The authors also established clinical parameters to define high risk with external rotation strength at less than or equal to 20.3% of body weight and abduction strength at less than or equal to 35.4% of body weight, which could be useful data for assessing injury risk and improving strength in high-risk individuals. Decreased hip strength has been shown to cause a valgus drift during stabilization when landing from a jump and this valgus load is known to place a great amount of strain on the ACL (10,21). Interestingly, decreasing hip strength has been observed in female soccer athletes during the transitional period from adolescence to late-teens, indicating that a hip strengthening program may be beneficial for this population (22). Furthermore, when considering lower extremity muscle strength overall, Ryman Augustsson and Ageberg observed that high school female athletes in the weak group of this study had 7 times the risk of sustaining an ACL injury compared to females in the strong group, but a difference in risk between groups was not seen in males (23). The above-mentioned neuromuscular and biomechanical deficits as well as the imbalances in muscular strength and activity have all been shown to be more common occurrences in females (10). Moreover, females have naturally greater knee valgus positioning and deficiencies in hip and core stability, and female athletes experience single-leg dominance more frequently than males, which is an additional risk factor of ACL injury (10). Finally, important modifiable extrinsic risk factors to consider include type of sport, fatigue and overuse without ideal recovery time, and suboptimal physical conditioning. Addressing these factors can also greatly influence ACL injury prevention without the need for an established program.

Prevention strategies

Effective training aspects

Given the significant role of neuromuscular control in noncontact ACL injury risk combined with an inherent ability to modify associated risk factors, effective prevention programs include multicomponent exercises targeted to improve neuromuscular deficits and movement patterns. In particular, such programs aim to reduce dynamic valgus and landing forces, and optimize muscle activation and strength imbalances to decrease overall injury risk during jumping, landing, and cutting movements. A recent 2019 systematic review of randomized controlled trials with meta-analysis of injury prevention programs reported that use of such programs led to a 53% overall reduction in ACL injury rates (24). In this extensive review, the authors found strong evidence that the most effective programs included plyometric, agility, and strengthening exercises. In a 2-part review of ACL injuries in soccer players, the authors reported that plyometric activities have been shown to be one of the most effective component of prevention programs (25). The preventative outcomes that result from plyometric training are related to improved landing mechanics, and some studies have specifically observed a decrease in knee valgus and increase in knee flexion at landing after implementing training (26). Related to plyometrics, the use of landing stabilization exercises during jump training have also been shown to be an effective aspect of ACL injury prevention programs (27). The direct efficacy of agility exercises on ACL injury prevention is an ambiguous topic, but several effective prevention programs include it as a training component. They appear to be more impactful when the agility exercises are sport-specific and are performed in combination with plyometric, strength, and balance exercises as part of a multicomponent program (28). Lower body strength training has also been frequently reported to be an imperative component of reducing ACL injury risk. As described by Acevedo *et al.*, specific targets to consider include the hamstring muscle and the gluteus maximus and medius muscles (11). The hamstring plays a significant role as an ACL agonist in preventing anterior tibial translation achieved by a higher ratio of hamstrings to quadriceps activity, which can be increased by eccentric strengthening exercises. Regarding the gluteus maximus and medius, optimizing muscle strength is important for decreasing femoral rotation and dynamic knee valgus during high-risk movements.

Separate analyses have also specified an importance of including balance training in multicomponent prevention programs (28). Proprioception is term often used when discussing balance exercises and it refers to the incoming signals on joint position. In the knee, this information is important for coordination of joint motion and interaction between complementary flexor and extensor muscles (10). Proprioceptive deficits can induce unwanted strain on the ACL caused by interruption of proper muscle activation. To improve these deficits, efficient balance exercises aim to increase dynamic stability and improve knee posture and control while in unstable positions (29). Balance training alone may not have a significant effect on preventing ACL injury, but it has been shown to enhance the outcome of an injury prevention program when combined with other types of exercises (28). Beyond the foundations of the effective training aspects crucial to injury prevention programs, there is room for flexibility in the specific exercises used. Among established injury prevention programs, they differ in how they are structured and delivered, but remain comparable in their overall success in reducing the risk of ACL injury.

Established prevention programs

The most important aspect to consider in reducing ACL injuries is utilizing injury prevention programs that contain multiple exercise components, including one or more of the aforementioned trainings. Furthermore, research has indicated high efficiency in implementing a preseason program at least 6 weeks prior to the start of the sport participation and continuing a lower intensity maintenance program throughout the competitive season that can replace a traditional warm-up (10,11). Many effective programs also provide an educational aspect for coaches, trainers, and athletes, such as a video and supplemental written materials, that exemplifies proper execution of the exercises included in the program and specific high risk movements to avoid. In addition to the program itself, studies have shown the importance of providing feedback, particularly placing emphasis on good technique and correcting errors, in effectively reducing ACL injury. A summary of different commercially available ACL injury prevention programs that have been developed in recent years and their direct influence on reduction of ACL injury rates in athletes are listed in *Table 1*.

Evidence-based suggestions for future injury prevention

Despite the substantial evidence of the effects of ACL injury prevention programs and their value in benefiting athletes, ACL injury rates have not successfully improved, primarily due to a lack of implementing programs (27). In a recent 2019 systematic review, Petushek *et al.* reported the use of neuromuscular prevention programs for ACL injury prevention to be as low as 13–20% nationally in female's sports teams at the high school level (27). Increasing public awareness and knowledge of the benefits of utilizing these programs can bridge the gap between research on the topic and standard use of prevention strategies, and successfully reduce ACL injuries in athletes. This can be achieved by improving communication between sporting associations and coaching staff, requiring mandatory education that targets the efficacy and ease of implementing programs, and providing trainers and coaches with access to proper resources (38). Similarly, Mehl *et al.* mentioned the potential for increased compliance of programs if the preventative exercises are combined with sport-specific exercises to create a more appropriate warm-up program for each respective sport (10). To provide examples, the authors described the following: jumping exercises for basketball, running exercises for football, and strength exercises for skiing. In addition to encouraging implementation of individual prevention programs, applying screening tests as a clinical standard early on and throughout athletes' careers has the potential to be a crucial component of targeted injury prevention. Multiple studies that have researched ACL injury risks performed prescreening tests in athletes prior to the start of their season and compared tested values between athletes that eventually suffered an ACL injury and those that remained uninjured during their season. Researchers were able determine risk factors related to ACL injury based on observations in the variations between neuromuscular control, biomechanical measures, and muscle strength. Based on this extensive research, readily available access to similar screening tests could provide athletes, parents, and treating physicians with valuable knowledge regarding individuals' specific risks for ACL injury. Examples of informational screening tests include the drop vertical jump test, which provides relevant data on an individual's biomechanics during landing, and use of a handheld dynamometer to test bilateral hip and knee strength in assessing imbalances (18,20,22). Furthermore, fatigue and overtraining without proper rest and recovery has been shown to increase risk of ACL injury.

Recently, Snyder *et al.* observed significant alterations in physical performance and biomechanical risk factors related to ACL injury in athletes participating in 2 soccer matches with less than 48 hours of rest in between (39). After the

Table 1 Summary of established prevention programs and their impact on anterior cruciate ligament (ACL) injury rates

Program	Training components	Duration and format	Reduction in injury rate	Reference(s)	Website
Prevent Injury and Enhance Performance™ (PEP)	3 basic warm-up activities, 5 stretching techniques for trunk and lower extremity, 3 strengthening exercises, 5 plyometric activities, and 3 sport-specific agility drills	20 min/session, 3 times a week, on-field warm-up to replace traditional warm-up	Up to 88%	Mandelbaum *et al*. (30)	https://la84.org/a-practical-guide-to-the-pep-program/
The "HarmoKnee" Program	Warm-up, muscle activation, balance, strength, and core stability	20–25 min/session, twice a week during preseason, once a week during regular season	70%	Kiani *et al*. (31)	http://www.harmoknee.com/
FIFA 11+	Part 1: initial running exercise session at lower intensity with forward, backwards, and sideways jogging, and active stretching	20 min/session, at least twice a week, standard on-field warm-up, only part 1 performed prior to matches	20–50% in the long term	Bizzini *et al*. (32), Al Attar *et al*. (33)	https://www.fifamedicalnetwork.com/lessons/prevention-fifa-11/
	Part 2: 6-set exercise session focusing on strength, plyometrics, and balance, with 3 levels of difficulty for each exercise Part 3: intensive running exercise session with more high-speed and change-of-direction running				https://www.fifamedicalnetwork.com/wp-content/uploads/cdn/20_years_of_fmarc.pdf
Knäkontroll (SISU Idrottsböcker, Sweden, 2005)	Low intensity running followed by 6 exercises focusing on knee control and core stability: one-legged knee squat, pelvic lift, two-legged knee squat, the bench, the lunge, and jump/landing technique; each exercise is subdivided into 4 steps of increasing difficulty (progression is sport-specific and based on feedback of good technique) and a partner exercise for variation	15 min/session, 2 times a week, on-field warm-up	64%	Hägglund *et al*. (34), Waldén *et al*. (35)	https://utbildning.sisuidrottsbocker.se/fotboll/tranare/spelarutbildning/knakontroll/
Sportsmetrics™	Stretching, jump training exercises/plyometrics, strength and weight training, and sport-specific agility drills	90 min/session, 3 times a week for 6 weeks	3.6 times higher injury incidence in untrained female athletes *vs*. trained female athletes	Hewett *et al*. (36), Barber-Westin *et al*. (37)	https://sportsmetrics.org/

first match, some increase in ACL injury risk was observed, but after the second match, these risk factors became more prevalent in addition to an increase in other risk factors, which the authors related to fatigue and cumulative effects. Similarly, Ryman Augustsson and Ageberg mentioned a particular concern for talented youth female athletes participating in additional soccer matches with higher level teams, where the added sport activity with minimal recovery time significantly increases ACL injury risk (23). With this risk of overtraining and the substantial effects that increased training loads can have on ACL injury risk, individual player monitoring in the form of wearable technology has become increasingly popular in the recent years (8). This equipment is able to measure training loads, accelerations and decelerations, and heart rate, and can be used by trainers to manage the pace and elements of practices as needed in order to improve performance and reduce injuries.

Conclusions

With the expanding knowledge of the epidemiology and noncontact mechanisms related to ACL injuries, the effort to improve injury prevention has also increased. Evidence-based prevention programs have been established in recent years that aim to modify risk factors associated with ACL injury. Extensive research on their effectiveness has been presented, which provides sporting associations, coaches, athletes, and healthcare providers with relevant information on reducing injury risk when properly executed. Separate from established programs, utilizing additional prevention techniques and minimizing athletes' exposure to avoidable risk factors can greatly reduce the likelihood of sustaining an ACL injury. To successfully decrease incidence rates of ACL ruptures in the near future, more emphasis must be placed on the importance of implementing these intervention strategies as a standard requirement in high-risk sports at every level of competition. Please find a supplemental Q&A between the authors and editors in Supplementary file.

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Supplemental questions

1. Dr. Sommer Hammoud: Can you summarize (in a table possibly) for the readers a few of the most promising wearable technologies currently in use or on the horizon, including how they are worn by the athlete and what they measure? Please provide your thoughts on the potential impact you think these may have

Author's answer: These systems have the ability to assess and profile individual injury risks, and give us a better understanding of athletes' workload and its influences on injury. In turn, we can apply this information to injury prevention based on results and observations. This real-time feedback on movements and mechanics gives us the opportunity to determine the most effective interventions that can be tailored to the individual athlete, ultimately addressing our goal to reduce the risk of injury.

Wearable technology	How it is worn	Measures
ViPerform™ (dorsaVi, USA)	3D wearable sensors placed on lower back and lower extremities	Range of movement (knee valgus/varus and trunk), symmetry, balance, and time measured on 3 planes of motion during movement tests and translated to a score indicating the level of injury risk
VICON IMeasureU Blue Trident Sensors & IMU Step Software (IMeasureU, New Zealand)	Body-worn sensor device on a strap and worn on lower leg(s)	Lower limb internal (ligaments, bones, other tissues) and external (body) load distributions
The Opal™ & Moveo Explorer Software (APDM Inc., USA)	Body-worn sensor devices on straps and worn on lower back, upper legs, lower legs, and feet	Lower limb kinematics, including knee flexion-extension, varus-valgus, and internal-external rotation
MilestonePod (Milestone Sports, USA)	Shoe-worn device	Running metrics, including foot strike, rate of impact, cadence, stride length, performance metrics

2. Dr. Sommer Hammoud: Do you think screening for the high school or small college that has only one athletic trainer is feasible? Do you have any suggestions for implementation at this level?

Author's answer: Screening is very difficult in the setting of a lack of adequate resources. Education with local athletic trainers and physical therapists can be helpful, but this is still an ongoing challenge. If dedicated screening isn't possible, making coaches and trainers aware of the ease of implementing interventions that can be integrated in daily warm-ups can still effectively address injury prevention.

3. Dr. Sommer Hammoud: Which screening methods and prevention programs do you use for your athletes at the high school and collegiate level?

Author's answer: We use pre-season screenings to get a baseline assessment on our college athletes, and employ an active warm-up strategy for all practices and games.

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