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ACL Injury Prevention: What Does Research Tell Us?

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Abstract
Purpose of Review Mechanisms leading to anterior cruciate ligament (ACL) injury have been identified, yet re-injury or a secondary injury persists in the athletic population. The purpose of this review is to identify risk factors associated with ACL injury and investigate programs to prevent injury.
Recent Findings Faulty mechanics during dynamic movement that cause excessive valgus force at the knee increases the risk of ACL injury. Faulty mechanics may be a result of lateral displacement of the trunk, unequal limb loading, and lack of control to avoid the valgus knee position. Altered movements that place the ACL at risk are best identified in a fatigued state; however, could be recognized in a standard dynamic assessment. The faulty movement patterns are modifiable and should be addressed in an injury prevention program. Prevention programs include various modes of exercise such as plyometrics, neuromuscular training, and strength training.
Summary This review concludes that those programs which utilize neuromuscular training and strength training at a young age show the most promise in reducing ACL injuries. An ongoing thorough dynamic examination is necessary for all athletes while adjusting the intervention program in order to decrease the risk of ACL injury.

This article is part of the Topical Collection on *ACL Rehab*

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Introduction

Although the incidence of anterior cruciate ligament (ACL) injury is unknown [1], it is estimated that 350,000 ACL reconstructions (ACLRs) are performed annually in the USA [2]. Despite surgical repair, approximately 79% of those individuals develop knee osteoarthritis (OA) and 20% suffer re-injury within 2 years [3]. The risk of re-injury and developing arthritis has become an economic burden and overall concern in the athletic arena [4]. Athletic ACL injury rates are increasing [5] in both D1 career athletes [6] and youth athletes [7]. One in four youths who suffer an ACL injury will suffer a second ACL injury in their athletic career [7]. Athletes who suffer a knee injury prior to participation in D1 career have an eightfold increased risk of suffering another knee injury during their D1 career and spend 50% more time on the disabled list (DL) [6]. Despite the ongoing research to identify contributing factors to potential knee injury in athletes, injury continues to occur and intervention and prevention models fail. As a result, knee injury (specifically ACL) has a large impact on future athletic performance. An accurate functional assessment tool and intervention are needed to curb this injury trend and identify factors that predispose athletes to injury.

Functional Anatomy and Biomechanics of the Knee

The ACL, extending from the lateral femoral condyle to the crest of the anterior medial aspect of the tibia, contributes to knee stability via passive restraint. The orientation and direction of the bands of the ACL act as a biomechanical restraint for rotation as well as limiting anterior translation of the tibia on the femur [8]. The combination of active muscle contraction with precise neuromuscular timing assists with knee stability during running, jumping, and cutting or pivoting maneuvers. Any alteration in the biomechanics or muscular control of the knee increases the risk of ACL injury.

Structural features of the knee that increase risk of injury to the ACL include intercondylar notch size as well as the integrity of the menisci. These factors, although only modifiable via surgery, should be recognized as potential causes of ACL injury. The intercondylar notch of the femur, especially in females, can be a structural risk if too narrow, resulting in compromised space for the ACL during rotation. The depth and integrity of the menisci assist condylar motion as the femur maintains contact during loaded motions such as flexion and rotation. A meniscus tear can alter the translation of the femoral condyles on the tibia and place added stress to the ACL during cutting or jumping maneuvers [9]. Other passive restraints such as joint capsule and ligamentous structures (i.e., collateral ligaments) control dynamic motion and assist with knee stability. Injury to any passive restraint in the knee may compromise the biomechanical function of the knee and increase injury risk to the ACL. It should be noted that tibial slope has been identified as a potential structural risk factor in ACL injury as well.

Dynamic and modifiable biomechanics of the knee such as hyperextension, excessive valgus, or abduction moments attribute to ACL stress. Stress on the ACL is the greatest with internal tibial torsion near full knee extension [9]. Cadaveric studies assist in further understanding the biomechanics of the knee by providing positions of the knee where the ACL is under stress. The ACL resists rotational forces at 10 and 30° knee flexion in cadaveric specimens and less at greater degrees of flexion such as 50–90° [10, 11]. However, dynamic muscular influences such as quadriceps dominance during sustained flexion activities causes anterior translation of the femur on the tibia and could predispose the ACL to stress [12,13,14•]. Effective co-contraction of the hamstrings and quadriceps has been postulated to assist in preventing the magnitude of anterior displacement that may occur with flexion activities such as cutting and landing from a jump [12, 15]. Double-limb or single-limb landing with an extended knee combined with abduction moments provides the greatest force to the ACL [14•,15•,16] (Fig. 1). As the knee accelerates into a valgus position, stress increases on the ACL. Additionally, poor muscular control results in improper knee alignment and increased anterior-posterior translation or rotary shear forces. This shear force and excessive rotary laxity can result in meniscus tears and injury to the ACL.

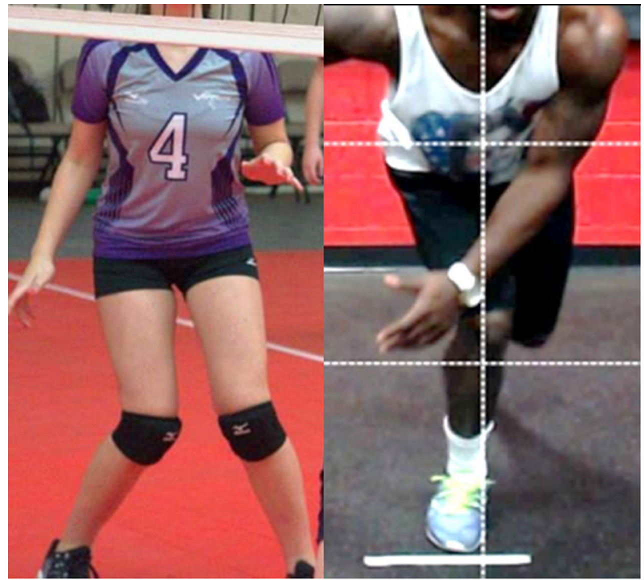

Fig. 1 Landing with knee extended and adduction moment causing stress to the ACL

Injury Prevalence

Injury to the ACL occurs during dynamic activities that primarily involve cutting and pivoting and can occur during landing after a jump. Competitive and recreational athletes between the ages of 15 and 25 are at the greatest risk of injury. The majority (80%) of the injuries are non-contact, and therefore, the mechanisms are modifiable [3, 17–19]. Female athletes are at risk four to six times greater than their male counterparts [20–22]. Female high school athletes had a ninefold increase injury risk and fivefold in collegiate sports [23] and those that competed at a higher level of play had a five times higher risk than their male counterpart [24]. Sports that require high dynamic loading of the knee and report a high incidence of injury include soccer, volleyball, handball, and basketball.

Associated consequences for both athletes and military personnel who suffer an ACL injury include time on disabled list or loss of duty time, increased risk of another injury, and development of OA [25–27]. Unique to the military, females were not more susceptible to primary ACL injury when compared to male personnel. Overall, prior knee injury in all military personnel contributed to risk of another knee injury and prior hip injury increased risk of specific ACL injury [28]. Re-injury in the athletic population occurs in one of four youths, and ACL graft rupture was higher in male athletes following repair when compared to female athletes who had ACLR [7, 29]. A 12-year follow-up study was conducted on 221 individuals post-ACLR and detected chondral defects (64%) and patellofemoral OA (26%) indicating continued degeneration of the knee joint and adjunct joints [30]. Holm et al. (2012) [3] conducted a 10-year follow-up on 57 patients who had ACLR, and 79% had developed OA. Despite surgical intervention, individuals who suffered ACL injury developed OA and reduced function [30].

Movement and Factors Impacting Performance

Frontal Plane Motion

Excessive adduction moment at the knee in the frontal plane increases injury risk to the ACL [31, 32]. Landing from a drop jump and cutting maneuvers in sports are correlated with increased adduction moment at the knee. The drop jump may be performed with single leg or double leg while the cutting involves a single limb. Therefore, the kinematics and kinetics are different for each of these activities [33]. A single-leg technique, such as the sidestep cutting maneuver, those with poor mechanics demonstrate six times the amount of frontal plane adduction moment when compared to the drop jump [34]. The amount of frontal plane adduction moment can be reduced or controlled to decrease the risk of injury to the ACL [35•], and analysis of single-leg motion should be included as an assessment in sports injury prevention.

Fatigue and Single Limb Testing

Fatigue has been related to increase risk of injury in the athletic population [36]. Athletes demonstrate increased motion in both the sagittal plane and frontal plane accompanied by greater ground reaction forces when fatigued [37]. The hip and knee internal rotation increased with fatigue creating a valgus force at the knee [38] and ground reaction forces increased with a single-limb hop [39]. The combined increased ground reaction force and valgus at the knee predisposes the ACL to injury.

Trunk Stability

Trunk position and hip motion strongly influence knee control during single limb and cutting motions [40•]. Decreases in trunk and hip strength and endurance result in larger center of mass (COM) displacement in athletics [41]. Increased control of trunk and hip sagittal and frontal motions reduces COM displacement and frontal plane motion at the knee [41, 42]. This improvement in COM has been directly correlated to improvements in pitching mechanics [41] and decreased injury rates in major league baseball players [43]. Targeted training to the hip and trunk has been shown to improve frontal plane motion at the knee and improvements in athletic performance measures [44].

Limb Symmetry Index

The standard of practice for assessing an athlete's ability to return to play is to assess their affected limb in comparison to their unaffected limb or to assess their limb symmetry index (LSI). LSI is a percentile measurement comparing the limb symmetry of the affected side to the unaffected side. Figure 2 shows the calculation for LSI [45].The LSI has been utilized as a quantitative measure to determine the strength and performance of an athlete prior to return to sport [46–48]. Non-injured athletes have a LSI of 90–95% [49], while individuals who suffer an ACL injury rarely reach greater than 90% LSI post reconstruction [50]. Although this has been primarily tested in an open kinetic chain, closed kinetic chain testing has been shown to be a better predictor of true limb symmetry [51–55].

Lateral Displacement of the Pelvis During Squatting Motion

The squatting motion is an essential movement for the development of lower extremity strength, endurance, and the explosive power associated with sports. Variations in weight distribution during this motion will impact joint and ligamentous loading, soft tissue and ligamentous strain [56], and influence asymmetry in strength development. Lateral displacement of the pelvis occurs during a squatting motion results in altered force distribution and joint forces [57•]. Peak ground reaction force has been calculated up to 3–6 times body weight during sporting activities [58]. A lateral shift of the pelvis with the increased ground reaction force alters distribution of loads through the lower limb, ligamentous structures, and lumbar spine and increases the likelihood of ligamentous and soft tissue injury, such as ACL injuries [58]. The altered length tension relationship of the musculature during training with poor mechanics leads to decreased force production. However, with proper education and rehabilitation, correction of lateral displacement of the pelvis is correlated with improved vertical jump height and sprint speed [59].

Prevention Programs

Many different programs have been developed with the goal of decreasing the risk and/or preventing ACL injuries [14, 22, 60, 61] (Table 1). There is a strong evidence in support of ACL injury prevention programs demonstrated by a risk reduction of 52% in the female athletes and 85% in the male athletes [22, 60, 71, 72]. Grimm et al. (2014) [61] reports a reduction in risk for knee injuries in soccer players and effectiveness of the use of intervention programs. Moreover, ACL injury prevention occurred when female athletes participated in a prevention program using specific training components [73].

Sugimoto et al. (2015) [74] has proposed six critical principles to follow when developing an ACL injury prevention program. These principles include age, biomechanics, compliance, dosage, feedback, and exercise.

LSI = Affected limb/unaffected Limb X 100%

Fig. 2 Equation for calculation of limb symmetry index

Table 1 Commonly cited injury prevention program articles

Study	Journal	Year	Subjects	No. of subjects	Sport	Program type	Duration	Frequency	Incidence of ACL injury per 1000 occurrences
Ghilchrist et al. [62]	AJSM	2008	Female	583 trained 852 control	Soccer	M-F approach[a]	20 min/session	3 days/week, entire season	0.057 trained group 0.189 control group
Caraffa et al. [63]	KSSTA	1996	Male	300 trained 300 control	Soccer	N-M approach[a]	20 min/session	Entire season	Not reported
Heidt et al. [64]	AJSM	2000	Female	42 trained 258 control	Soccer	M-F approach[a]		2 days/week 7 weeks	0.25 trained group 0.33 control group
Hewett et al. [65]	AJSM	1999	Female/male	366 trained 463 control	Soccer Volleyball Basketball	M-F approach[a]	60–90 min/session	3 days/week, 6 weeks	0.12 trained group 0.22 control group
Mandelbaum et al. [66]	AJSM	2005	Female	1885 trained 3818 control	Soccer	M-F approach[a]	20 min/session	3 days/week, 12 weeks	0.09 trained group 0.49 control group
Peterson et al. [67]	AOTS	2005	Female	134 trained 142 control	Handball	N-M approach[b]		3 days/week, 8 weeks	0.08 trained group 0.49 control group
Pfeiffer et al. [68]	JBJS	2006	Female	577 trained 862 control	Soccer Volleyball Basketball	Plyo approach[c]	20 min/session	2 days/week, entire season	0.078 trained group 0.167 control group
Kiani et al. [69]	AIM	2010	Female	1506	Soccer	M-F approach[a]		2 days/week pre-season, 1 day/week in-season	0.04 trained troup 0.20 control group
Soligard et al. [70]	BJSM	2008	Female	1055 trained 837 control	Soccer	M-F approach[a]	20 min/session	entire season	Not reported

AJSM American Journal Sports Medicine, *KSSTA* Knee Surgery, Sports Traumatology, Arthroscopy, *AOTS* Archives of Orthopedic and Trauma Surgery, *JBJS* Journal of Bone and Joint Surgery, *AIM* Archives of Internal Medicine, *BJSM* British Journal of Sports Medicine

[a] M-F approach: multi-faceted approach included a warm-up, strengthening, plyometrics, and agility activities

[b] N-M approach: neuromuscular approach included proprioceptive, balance, and stability activities

[c] Plyo approach: plyometric-based approach included jumping and cutting activities

Six Principles of a Prevention Program

Age It is recommended that ACL prevention programs be implemented at an early age. Fewer ACL injuries were documented in younger athletes who performed a neuromuscular training program compared to older athletes who performed the same program [66, 75•, 76].

Biomechanics Faulty biomechanics correlated with increased strain on the ACL during different movement patterns and sporting activities with increased knee valgus being one of the strongest indicators of increased ACL injury risk [73, 77•, 78, 79].

Compliance Compliance of performance of an ACL prevention program is vital to the ability of the program to be successful at reducing injury rates. Compliance greater than 66% resulted in an ACL injury reduction rate of 82%. However, when compliance rate dropped to less than 66%, ACL injury reduction rate dropped to 44% [80]. Currently, compliance is subject to a large degree of heterogeneity in literature and the need to have a uniform definition is needed [81].

Dosage Frequent participation in an ACL prevention program decreases risk for ACL injury. Most studies agree that each session should be between 20 and 30 min and should be performed several times per week. Optimally, they should be initiated in the pre-season and continued throughout the season to attain the full effectiveness of the program [60, 82].

Feedback Many studies included some type of feedback, and whether verbal or visual, a decrease in ACL injuries has been shown. Feedback can be in the form of verbal cueing from a coach or a training partner, but can also be visual as in a training video. Feedback should also come in the form of an external focus versus internal focus. External focus is directed toward the outcome or effects of the movement, assists the automation of movements, and accelerates the learning process. When teaching proper landing mechanics, an external focus command would be, "Try to bring your knees as close to the outside walls as possible when you land" [83]. Internal focus is directed toward specific movements, such as "keep your knees out," and this constant focus on correct movement can lead to a reduction in athlete's motivation. Thus, it is recommended that a feedback system be implemented in an ACL prevention program with an external focus [62, 76, 83–85].

Exercise Variety ACL injury prevention programs that included a variety of different exercises have a greater incidence of decreasing injury risk versus programs that include only one type of exercise or component (plyometric, balance, strengthening). These exercises can be mainly classified into three different components: plyometrics, neuromuscular training, and strength training. All three have been utilized as stand-alone programs or have been combined to create comprehensive prevention programs [21, 61, 86•].

Three Components of Exercise in a Prevention Program

Plyometrics Plyometrics focusing on proper technique and body mechanics can help to reduce serious ligamentous injuries, specifically ACL injuries [65, 68].

Neuromuscular Training The term neuromuscular training is utilized throughout the literature and is included in most injury prevention programs [62, 65, 87] (Table 1). The objective of neuromuscular training is to improve the ability to generate optimal muscle firing patterns, increase dynamic joint stability, and to perform movement patterns and skills necessary during activities of daily living and sports activities. This may include balance exercises, proprioceptive activities on balance and wobble boards [63, 87], single-leg stability activities [66, 73], dynamic joint stability exercises, jump training, plyometric exercises, agility drills, and sport-specific exercises [88, 89]. These types of proprioceptive and balance training can improve postural control and side-to-side imbalances in lower extremity measures [90].

Strength Training The programs that incorporated strength training were among the most effective at decreasing ACL injury rates; however, strength training alone may not be efficacious for prevention. Programs have been shown to be effective in decreasing ACL injures without the usage of strength training [67, 68, 91]. Resistance training may aid in the reduction of ACL injuries when combined with other training components; however, the efficacy of a single-faceted resistance training protocol on ACL injury prevention has yet to be determined [14].

Conclusion/Summary

Injury to the ACL is the leading knee complication in sports and the primary cause of time on the disabled list.

Modifiable factors such as excessive frontal plane motion leading to dynamic valgus forces at the knee and improper landing or cutting techniques directly stress the ACL and contribute to the risk of injury. The authors recognize that valgus stress at the knee associated with poor neuromuscular control and trunk position predisposes the athlete to injury especially in a fatigued state. However, terminology in the literature varies how this position is described. Abduction moment of the knee and adduction moment were both utilized to describe a valgus force depending on the reference of orientation of tibia on femur (distal to proximal) or femur on tibia (proximal to distal). Despite the discrepancy, the resultant valgus stress at the knee with limited neuromuscular control is the largest risk for ACL injury and is a modifiable mechanism utilized in prevention programs.

A dynamic assessment is recommended for evaluating athletes at risk for ACL injury. Faulty mechanics especially in a fatigued state can assist in identifying alterations in the trunk, pelvis, and lower kinetic chain during functional movements that may predispose the athlete to injury. Herein, the development of specific interventions can be established and incorporated into a prevention program that is specific to the athlete.

Some prevention programs utilize a multi-faceted approach or neuromuscular approach while others utilize strengthening and plyometrics. Programs that integrated strengthening with neuromuscular training were the most effective, and incorporating this method at a younger age was beneficial for injury prevention. Time spent in the prevention program has yet to be standardized for the most effective outcomes, though currently, most studies agree that 20–30min sessions several times weekly are needed. Further work is needed to establish the ideal approach for ACL injury prevention programs.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflicts of interest.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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