Introduction

High school athletics can provide a great medium for improving physical fitness and has recently been found to be the best predictor of physical activity after age 70.[1] Sports participation has also been associated with increased academic performance.[2] Unfortunately, participation in athletics also carries an increased risk of injury. In general, knee injuries account for approximately 15.1% of all high school injuries.[3] Of those, 16.9% occur specifically to the anterior cruciate ligament (ACL),[3] with 75-95% being non-contact ligament ruptures.[4,5] Females are disproportionately affected by ACL injuries, with data showing a female-to-male injury ratio of 3:1 in basketball and soccer, and 4:1 in softball/baseball.[5] More than any other injury, ACL ruptures typically lead to the end of an athletic season and subsequent reconstructive surgery. While surgery is currently the best treatment option for young athletes to return to sport, the injury can negatively affect their psychology[6] and increases the likelihood of future orthopedic issues.[7] Also, the economic burden placed on families and the medical system can be substantial.[3]

Despite current reconstructive and rehabilitative advancements, an athlete's short- and long-term outlook still appears grim. In the 24 months following reconstructive surgery, athletes carry a six-times greater risk of subsequent ACL injury compared to healthy counterparts.[8] Studies on long-term effects of ACL reconstruction have shown greater increases in knee degeneration and osteoarthritis within 10 years of surgery compared to healthy controls.[7] These long-team effects can be costly for high school athletes suffering an ACL injury, with lifetime bills reaching upward of $40,000.[9] Clearly, the prevention of ACL injuries should be a priority amongst high school athletes to prevent future risk and lower economic burden.

Physicians continue to see increases in ACL injuries with subsequent increases in reconstructive surgeries.[10] These increases have been attributed to increased sport participation, particularly high-demand sports, and participation starting at an earlier age. Also, improved clinical and radiological diagnostics and increased awareness of ACL injuries are factors leading to increased identification of pathology.[11] It's likely sports participation will not change, therefore sports medicine professionals should turn to risk factor screening and injury prevention. ACL prevention programs have gained popularity, but literature reviews have shown mixed results in decreasing ACL injury incidence.[12] Significant methodological heterogeneity appears within these programs making it difficult to judge their overall effectiveness.[12] However, some positive results encourage further exploration into the important components of these programs.

ACL injuries have remained one of the most highly studied conditions in sport and orthopedic research, with more than 1,100 manuscripts published in 2013.[10] The purpose of my capstone is to investigate risk factors associated with non-contact ACL injury in high school athletes. After identifying risk factors, I will further investigate screening tools and key prevention programs components that can used as part of comprehensive ACL prevention strategy for sports medicine professionals.

ACL Mechanism of Injury

Non-contact ACL ruptures are defined as injuries occurring with no physical contact with another player at the time of injury. They most often occur when an athlete is landing, changing direction, or decelerating on a planted foot.[4,13,14] During these movements, position of the body will dictate how forces are attenuated in the lower extremity. Landing or cutting with an upright posture and an extended hip and knee often leads to increased vertical ground reaction forces and quadriceps activation, which can cause large anterior shear forces on the ACL.[4,5,15] Quadriceps force at small knee flexion angles are likely the primary contributor to ACL loading.[4,5] Anterior translation of the tibia in combination with transverse (tibial internal/external rotation) or frontal (abduction/adduction) plane movement, further increases ACL strain and the likelihood of rupture.[4] The "position of no return" has been described as landing with an extended hip and knee, knee in valgus, internal rotation of the tibia, and a pronated foot.[13] However, hyperextension and knee external rotation have also been attributed to ACL tear.[4] Lastly, landing with the center of mass behind the body, resulting in large internal knee extensor moments and subsequent quadriceps activation, has also been implicated in ACL ruptures.[4]

Figure 1. ACL injury showing one form of the mechanism of injury. *From Alentorn-Geli et al (2009).*[4]

ACL Risk Factors

Risk factors can be divided into two categories: external and internal. Extrinsic risk factors are "outside" of the athlete's body, including environment, shoe/surface interaction, footwear type, and competition level. Intrinsic risk factors are a result of an athlete's body, including anatomic alignment, developmental, hormonal, biomechanical and neuromuscular factors. Intrinsic risk factors can be placed into modifiable and non-modifiable categories. For ACL screens and prevention programs, modifiable intrinsic risk factors that can show improvements over time and are most meaningful. The primary focus for my capstone will be on these risk factors. However, I will briefly touch on other external and non-modifiable internal risk factors to provide a complete overview.

External Risk Factors.

Environment, shoe/surface interaction, footwear type, and competition level are all extrinsic risk factors for ACL injury. Weak evidence suggests dry weather carries a higher risk of ACL injury compared to wet weather.[4,13] Theoretically, drier weather results in higher shoe/surface friction and traction compared to a wet surface, which could increase torsional forces through the lower extremity.[4] Differences in playing surface also alter shoe/surface interaction. Artificial turf has been associated with a greater risk of ACL tears compared to natural grass.[4,13] For natural grass, thicker thatch layers in Bermuda grass make it associated with a higher risk of ACL injury compared to rye grass.[4,13] Cleats with longer and greater number of spikes has been associated with a higher ACL injury rate.[4,13] There appears to be a higher rate of ACL injuries in college level competition compared to high school competition.[16] Overall, studying external risk factors in ACL injuries is challenging because many confounding variables cannot be controlled.

Non-Modifiable Internal Risk Factors.

As mentioned previously, girls are at a greater risk of ACL rupture compared to boys in sports involving cutting and jumping, like basketball and soccer. Some have suggested hormonal and anatomic differences between males and females contribute to this increased incidence. The human ACL contains estrogen and progesterone receptors. It has been suggested the female menstrual cycle may affect the laxity of the knee during certain phases of the cycle. While research hasn't provided a clear answer, a systematic review by Hewett et al (2007) suggests an increased risk of ACL injury during the first half (preovulatory phase) of the menstrual cycle.[17] Interestingly, their report indicates ACL mechanical properties are not changed by hormones during of the menstrual cycle, rather, other neuromuscular factors (strength, movement patterns, etc) may be affected by estrogen, which results in an increased risk of injury.[17] However, other groups have found anterior knee laxity to increase during the ovulatory or post-ovulatory phases of the menstrual cycle.[4] Oral contraceptives have been associated with decreased risk of ACL injury, however more clinical studies must be performed to understand if a causal relationship exits.[18] At this point, hormonal effects appear to increase the risk of ACL injuries in females, although the specific mechanism is less understood. Protection could come in form of preventative strategies that would improve dynamic stability of the knee joint.

Anatomic risk factors for ACL injury have been studied extensively, but practitioners have a limited ability to change their influence. Femoral notch width has been investigated as a potential risk factor. The ACL passes between the femoral notch as it spans from the posterior medial side of the lateral epicondyle to the anterior tibial plateau. Regardless of gender, some research has indicated a narrower notch size has been associated with increased risk of noncontact ACL.[13] Other research has not connected notch size with an increased risk of ACL injury.[14] Further research is necessary to fully understand femoral notch implications. The Q-angle, formed by one line from the ASIS to the center of the patella and another from the center of the patella to the tibial turbercle, has been suggested as a risk factor by many.[4,13,14] In general, the Q-angle is larger in females compared to males due to a wider pelvis in women.[14] Recent studies have not been able to find an association between Q-angle and an increased risk of ACL injury.[4] Additionally, the Q-angle likely changes with activity, which invalidates the measure in my opinion.[14] Since altering gender, hormonal, and anatomic factors are outside of a physical therapists' scope of practice, no further discussion is warranted.

Previous injury is consistently found to increase the risk of future ACL injury. A systematic review by Fulton et al (2014) found 10-12% of athletes will reinjure their reconstructed or contralateral ACL.[19] Paterno et al (2012) found the incidence rate of an ipsilateral or contralateral injury to the ACL following reconstruction to be 15 times greater compared to healthy controls without injury.[8] The same study found female athletes to be four times more likely to suffer another ACL injury to the reconstructed graft and six times more likely to suffer an ACL injury to the contralateral knee compared to male athletes.[8] Inadequate rehabilitation and prevention programs have to garner some responsibility for such high re-injury rates in athletes following ACL reconstruction. Screening and prevention programs would help identify athletes at risk of future injury.

Modifiable Internal Risk Factors.

In general, females have more general ligamentous laxity than males.[14,20] A prospective study by Uhorchak et al (2003) found joint laxity to be a risk factor for ACL injury in male and female military cadets.[21] Myer et al (2008) found increased anterior-posterior knee joint laxity, side-to-side differences in joint laxity, and knee hyperextension to be associated with increased risk of ACL injury.[22] A study by Vaishya et al (2013) found an increased presence of general joint hypermobility (using the Beighton score) in patients who had suffered an ACL rupture compared to healthy controls.[23] A recent study by Junge et al (2015) investigated relationships between generalized joint hypermobility and it's influence on a single leg hop task in 10-15 year old athletes.[24] Subjects with generalized joint hypermobility showed altered muscle activation patterns during landing with higher reliance on the gastrocnemious compared to the hamstrings.[24] This neuromuscular pattern has been associated with increased strain on the ACL.[24] All of these studies imply a need for increased knee stability in individuals with general joint hypermobility. A recent study by Shultz et al (2015) demonstrated increased knee laxity with fatiguing exercise, which is a common characteristic of sport in later stages of a game or practice.[25] While joint laxity or hypermobility is likely related to genetic disposition, motor control factors and exercise, neuromuscular and fitness training has been suggested to help improve joint stability by training muscles to be dynamic restraints.[26] Assessing general joint hypermobility, particularly knee hyperextension, may be component of ACL injury risk screening.

Differences in neuromuscular control of the body have been associated with increased loading of the knee and ACL. The amount of strain placed on the ACL during sporting movements is related to forces imposed on the ligament and timing of ground reaction forces.[15] Therefore, not only is total force imposed important, but also the rate at which it is applied. As mentioned previously, altered mechanics during high-risk movements could lead to rapidly imposed anterior shear forces in combination with frontal and transverse plane motion, leading to significant strain on the ACL.[4] Research on high-risk athletic movements like landing, cutting, or deceleration, have found gender-related differences in movement strategies in all three planes of motion. During these movements, females exhibit smaller knee flexion angles, greater knee valgus angles, and greater hip internal rotation angles, all with greater forces and torques.[5] Also, females tend to have lower gluteus maximus activity and greater quadriceps-to-hamstring activation ratio.[5] These alterations are associated with increased load at the knee and potentially increase the risk for ACL rupture. Male athletes may face the same neuromuscular control issues.[27] More prospective studies investigating ACL injuries would improve our understanding of neuromuscular risk factors.

One such study is a prospective study of female athletes by Hewett et al (2005). The authors were able to identify neuromuscular control differences between ACL-injured and non-injured athletes by assessing a jump-landing task at the onset of the study and comparing results of injured athletes to healthy athletes. Their research found knee abduction angles to be 8.4^{o} greater at initial contact, knee flexion angles to be 10.5^{o} less during landing, and vertical ground reaction forces to be 20% higher in ACL-injured female athletes.[28] Also, all of these differences occurred with a 16% shorter stance time, meaning increased motion, forces and moment all occurred more rapidly than their non-injured counterparts.[28] The authors found knee abduction moments to predict ACL ligament injury with 73% specificity and 78% sensitivity.[28] Another study by Lin et al (2009) used a stochastic biomechanical model to identify risk factors of ACL injuries.[29] The model was based off a stop and jump task, described as an athlete running and jumping off two feet similar to a basketball player jumping for a rebound. They found decreased knee flexion angles, increased posterior ground reaction forces, increased knee valgus, lower hamstring and gastroc muscle force and increased sagittal plane loading to be risk factors associated with ACL injury.[29] Both studies presented similarities and differences that are important to consider for developing screening tests for athletes. Based on the results of these studies, promoting hip, knee, and ankle flexion with limited frontal and transverse plane movement during landing or deceleration tasks could minimize the risk of ACL injury. Additionally, strengthening the quadriceps and hamstrings in functional, closed-chain exercise may prepare athletes to attenuate landing and cutting forces. Lastly, and maybe more important, assessing movement patterns appears necessary to help identify excessive motion in the frontal and transverse plane in athletes.

Trunk position has also been identified as a possible risk factor ACL injury. Research has shown a more upright and/or laterally flexed trunk is common during ACL injuries.[26] This position can alter hip extensor and knee flexor muscle function by altering length-tension relationships of the muscles. Increased trunk flexion results in lengthening of the hamstring and gluteus maximus muscles allowing them to produce an increased hip extension moment, reduced knee extension moment, and reduced knee valgus moments during landing.[26] Additionally, trunk position will affect the center of mass of the body, with decreased trunk flexion moving it posterior.[26] As mentioned previously, a posterior center of mass is described as part of the mechanism of injury for ACL ruptures because it increases quadriceps activation.[5] Feedback to athletes encouraging them to increase trunk flexion during landing has lead to decreased ground reaction forces in a number of studies reviewed by Hughes et al (2014).[26] Therefore, in addition to lower extremity movement patterns, sports medicine professionals should also assess trunk position when screening for movement patterns.

Hamstring muscle activation can effectively reduce shear forces on the ACL produced by the quadriceps during landing, cutting, and deceleration maneuvers. Co-contraction of the hamstrings with the quadriceps has been proposed an as important element of dynamic knee stability, including control of the transverse and frontal plane.[26] Therefore, weakness in the hamstring muscles could increase risk of ACL injury. Hewett et al (2006) propose proper hamstring activation is required for effective co-contractions with the quadriceps to create knee stability. Without quality hamstring activation, the quadriceps cannot activate properly, and increased ground reaction forces during sport movements will place increased strain on passive tissue structures, including the ACL.[30] This is supported by the stochastic biomechanical model of Lin et al (2009) where decreased hamstring activation coincided with increased forces in all three planes of motion.[29] Additionally, a systematic review by Shimokochi et al (2008) highlighted the danger of unopposed, excessive quadriceps force with reduced hamstring activation.[31] Asymmetrical activation of the hamstring muscles could also lead to decreased control of forces in the frontal plane, as studies have shown increased lateral hamstring activation leading to increased strain on the ACL in female athletes.[30] Wild et al (2013) actually displayed this in their study in adolescent females, where a group with lower peak isokinetic knee flexion force displayed altered lower extremity biomechanics during a landing task that would potentially increase strain on the ACL.[32] Optimal timing of hamstring muscle activation may be important to attenuate forces at the right time.[30] While research has focused often on hamstring strength, decreased quadriceps strength may also contribute to an inability to attenuate forces and strain on the ACL.[14,15] As an athlete prepares to strike the ground during an athletic movement, the lower extremity and core muscles pre-activate prior to foot contact. This pre-programming is necessary to help attenuate forces, but may be altered in athletes at risk of ACL injury.[30] Based on this information, a stronger, trained athlete may be better prepared for the rigors of competition. Assessment of lower extremity strength, particularly the hamstring group, may be an important consideration for sports medicine professionals.

Muscle fatigue has also been implicated as a risk factor for ACL injury. Shultz et al (2015) showed a repeated sprint protocol significantly alters landing biomechanics in both male and female competitive athletes.[25] Additionally, Iguchi et al (2014) demonstrated that fatigue-inducing exercise can alter unanticipated side-step maneuvers leading to decreased hip flexion at both initial contact and overall.[33] The alterations in biomechanical and neuromuscular control associated with fatigue are likely to increase the risk of ACL injury in athletes.[14,15] Assessing the fitness of athletes and testing their ability to execute high-risk movement patterns in a fatigued state may be important.

ACL Screening Procedures

There is a need for injury prediction screening measures that are time and cost-effective for sports medicine professionals.[28,34,35] Additionally, these screening tests should show sufficient psychometric properties including reliability, validity, and sensitivity. Screening tests, therefore, need to be quick, easy, have well-defined rating critieria, and require minimal equipment and/or technology. At the current time, there is not one screening procedure that fulfills all of these requirements for predicting an athlete's risk of ACL injury. Dallinga et al (2012) published a systematic review of lower extremity screening tests and only found two tests predictive of ACL injury.[36] Since their publication, new research has come out in support of other tests and a number of them have been predictive of ACL injury. This portion of my capstone will highlight some of these tests.

General Joint Hypermobility.

General joint hypermobility has been associated with increased risk of ACL injury.[4,22–24] The Beighton score for general joint hypermobility may be used to screen for this risk factor. Criteria for the test is defined in Table 1 below. Positive scores receive a '1' for each body part, with a total of nine scores added together for a composite score.

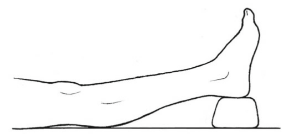
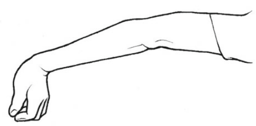
	Positive if 5th finger extends beyond 90 degrees. Test left and right.		Positive if the knee hyperextends > 10 degrees. Test left and right.
	Positive if thumb can be abducted to touch the forearm. Test left and right.		Positive if the subject can place palms flat on floor with knees straight.
	Positive if the elbow hyperextends > 10 degrees. Test left and right.	Positive scores are added up to create a composite score with a maximum of 9.	

Table 1. Beighton score for joint hypermobility criteria. ***Methods from Boyle et al (2003)[37] and images from Naal et al (2014)[38].***

Inter- and intra-rater reliability was found to be good to excellent for both the composite and specific category scores.[37] Scores are often placed into three ranges: 0-2, 3-4, and 5-9, with a score of 5 or greater representing general joint hypermobility. Beighton scores greater than 5 have correlated with increased joint hypermobility.[39] No research has been performed to identify whether comprehensive test scores could be used as a screening tool for ACL injury risk. However, as mentioned previously, Meyer et al (2008) was able to show a 5 times greater odds of ACL injury with positive knee hyperextension test.[22] The Beighton score may be useful in conjunction with other tests to characterize each athlete.

The Functional Movement Screen.

Dysfunctional movement patterns may be associated with increased injury risk in athletic populations. Evidence presented above shows less than optimal movement patterns are associated with increased loading of the ACL. The Functional Movement Screen (FMS) was developed to assess general movement proficiency and specifically identify dysfunctional movement patterns.[40] The screen consists of seven different tests: 1) deep squat, 2) hurdle step, 3) in-line lunge, 4) shoulder mobility, 5) active straight leg raise, 6) trunk stability pushup, and 7) rotary stability. Test descriptions and grading criteria are readily available through other resources[40] and pictures of the tests are seen in Figure 2 below. Each test receives a score of 0-3. A score of '0' indicates pain is present and the athlete should seek medical attention. A score of '1' indicates poor movement quality based on the criteria each test. A score '2' indicates acceptable movement quality based on the criteria each test. A score '3' indicates perfect movement quality based on the criteria each test. Originally, a composite score was used as a cutoff to predict injury (typically < 14/21), but recently the test's creator has advised practitioners using the screen to focus on individual test scores.

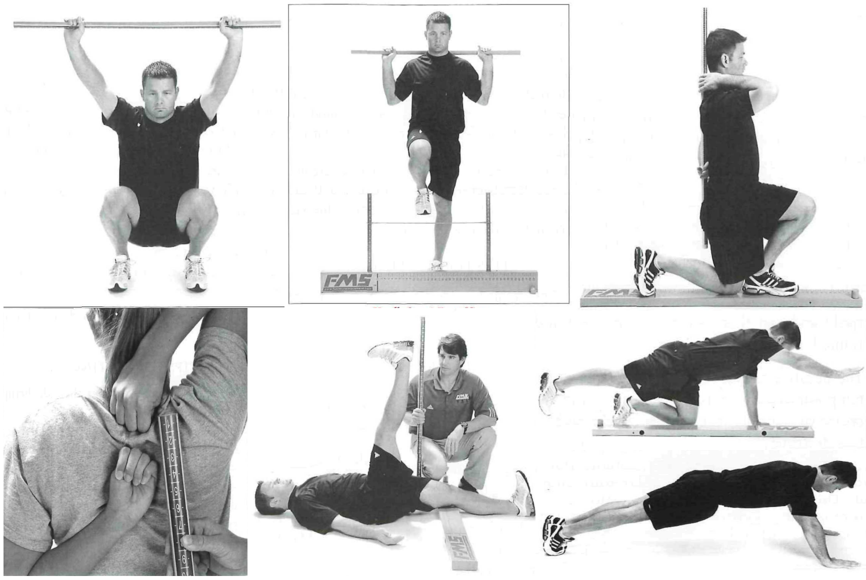


Figure 2. Functional Movement Screen tests receiving a '3' score. ***From Cook (2011).***

The Functional Movement Screen is the most commonly used test for identifying injury risk amongst international premier league soccer clubs, however evidence supporting it's use at that level of competition has relied mostly on expert opinion.[41,42] McCall et al (2015) reports some limitations including that test scores may change if the subject is aware of scoring criteria and adequate training in the test is required to improve reliability of testing.[42] Some studies have supported the FMS's ability to detect injury, especially specific tests. One relevant to this paper is by Zalai et al (2015), who found elite soccer athletes who suffered a knee injury during the a season scored significantly lower on the deep squat.[43] However, a small sample size is a significant limitation of this study. Additionally, a number of studies have shown the FMS to have variable sensitivity (8.3%-91%), suggesting more research is needed to truly determine the screens value in predicting injury.[44] No research has looked at the FMS's ability to specifically identify ACL injury risk.

The Landing Error Score System (LESS) and The Tuck Jump Assessment.

Proper force attenuation through optimal movement patterns during landing from a jump appears to be important for preventing ACL injury based on the neuromuscular and biomechanical risk factors presented above. Since many injuries occur during landing, screening tests incorporating jumping seems appropriate. The Landing Error Score System (LESS) and the Tuck Jump Assessment are two proposed screening tests that may be implemented on the field with minimal equipment.

The LESS was designed as a field assessment tool to identify high-risk movement patterns during a jump-landing task. The athlete starts on a 30-cm box. A line marked with tape is placed at a distance of half the athlete's height away from the edge of the box. To complete the jump-landing task, the athlete jumps forward so both limbs leave the box simultaneously, land just past the line, and jump for maximal height immediately after landing. Figure 3 below shows the jump-landing task in a laboratory setting. Each athlete performs the task three times. Two video cameras are required and placed 10 ft away from the landing area to record each jump in the sagittal and frontal plane.

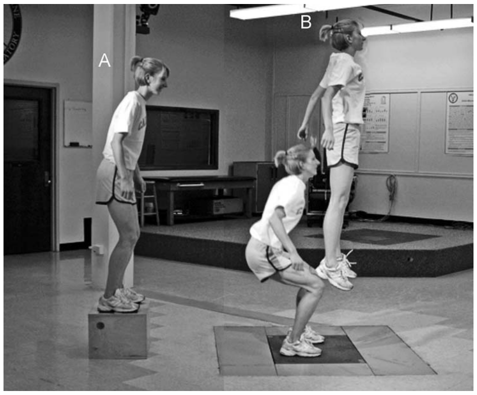


Figure 3. The subject jumps from the box to the landing area, then immediately jumps for maximal height. *From Padua et al (2015).*[45]

Analysis of the movement occurs at two points: 1) initial contact, defined as the frame immediately before the foot was flat on the ground, and 2) between initial contact and maximal knee flexion. Operational definitions of the LESS score items are defined in Table 2 below.

Landing Error Scoring System Item	Operational Definition of Error	Scoring
Knee flexion: initial contact	The knee is flexed less than 30° at initial contact.	0 = Absent 1 = Present
Hip flexion: initial contact	The thigh is in line with the trunk at initial contact.	0 = Absent 1 = Present
Trunk flexion: initial contact	The trunk is vertical or extended on the hips at initial contact.	0 = Absent 1 = Present
Ankle-plantar flexion: initial contact	The foot lands heel to toe or with a flat foot at initial contact.	0 = Absent 1 = Present
Medial knee position: initial contact	The center of the patella is medial to the midfoot at initial contact.	0 = Absent 1 = Present
Lateral-trunk flexion: initial contact	The midline of the trunk is flexed to the left or the right side of the body at initial contact.	0 = Absent 1 = Present
Stance width: wide	The feet are positioned greater than a shoulder width apart (acromion processes) at initial contact.	0 = Absent 1 = Present
Stance width: narrow	The feet are positioned less than a shoulder width apart (acromion processes) at initial contact.	0 = Absent 1 = Present
Foot position: external rotation	The foot is internally rotated more than 30° between initial contact and maximum knee flexion.	0 = Absent 1 = Present
Foot position: internal rotation	The foot is externally rotated more than 30° between initial contact and maximum knee flexion.	0 = Absent 1 = Present
Symmetric initial foot contact: initial contact	One foot lands before the other foot or 1 foot lands heel to toe and the other foot lands toe to heel.	0 = Absent 1 = Present
Knee-flexion displacement	The knee flexes less than 45° between initial contact and maximum knee flexion.	0 = Absent 1 = Present
Hip-flexion displacement	The thigh does not flex more on the trunk between initial contact and maximum knee flexion.	0 = Absent 1 = Present
Trunk-flexion displacement	The trunk does not flex more between initial contact and maximum knee flexion.	0 = Absent 1 = Present
Medial-knee displacement	At the point of maximum medial knee position, the center of the patella is medial to the midfoot.	0 = Absent 1 = Present
Joint displacement	Soft: the participant demonstrates a large amount of trunk, hip, and knee displacement. Average: the participant has some, but not a large amount of, trunk, hip, and knee displacement. Stiff: the participant goes through very little, if any, trunk, hip, and knee displacement.	0 = Soft 1 = Average 2 = Stiff
Overall impression	Excellent: the participant displays a soft landing with no frontal-plane or transverse-plane motion. Poor: the participant displays large frontal-plane or transverse-plane motion, or the participant displays a stiff landing with some frontal-plane or transverse-plane motion. Average: all other landings.	0 = Excellent 1 = Average 2 = Poor

Table 2. LESS scoring items and definitions. *From Padua et al (2015).*[45]

Higher scores indicate more errors in the athlete's movement pattern. Data from a prospective cohort study by Padua et al (2015) on male and female youth soccer athletes showed uninjured athletes had lower LESS scores in athletes who suffered an ACL injury compared to uninjured athletes.[45] Receiver operator curves suggested a score of 5 was the cut-point for the LESS with a sensitivity of 86%. The LESS has been shown to be reliable and valid.[46] Only one other study has used the LESS as a screening test to identify ACL injury risk. Smith et al (2012) used it as a screening test for high school and college athletes, but their study found no relationship between LESS scores and the risk of suffering an ACL injury.[47] However, in investigating the methods, the authors only had the subjects drop immediately off a box and jump rather than having the subjects jump off the box to a landing area half the subject's height. It is likely this would have decreased the ground reaction forces placed through the lower extremity and may have hidden abnormal movement patterns that would have identified if the LESS methods were followed.

The Tuck Jump Assessment has also been proposed to assess abnormal movement patterns within a repeated jumping task.[48] A tuck jump is when an athlete brings their knees to their chest during the ascent of the jump. For the assessment, an athlete performs a repeated tuck jump for 10 seconds. Figure 4 shows the demonstration of a repeated tuck jump.

Figure 4. Demonstration of a tuck jump. ***From Myer et al (2008).***[48]

The assessor visually grades the quality of the athlete's movements based on ten different criteria divided into three categories: 1) knee and thigh motion, 2) foot position during landing, and 3) plyometric technique. See Figure 5 with categories and associated pictures of poor technique.

Knee & Thigh Motion

1. Knee valgus on landing
   - Hip, knee and foot aligned, no collapse of the knee inwards
2. Thighs not reaching parallel (peak of jump)
3. Thighs not equal side to side (during flight)

Foot position during landing

4. Foot placement not shoulder width apart
   - Inside of tape marks
5. Foot placement not parallel (front to back)
6. Foot contact timing not equal
   - Asymmetrical landing
7. Does not land in same foot print
   - Consistent point of landing
8. Excessive landing contact noise

Plyometric technique

9. Pause between jumps
10. Technique declines prior to 10seconds

Figure 5. Criteria for the Tuck Jump Assessment and pictures show faulty movement patterns. ***From Herrington et al (2013).***[35]

If the athlete fails to meet the specific criteria, they are given a '1', while a '0' is awarded to the athlete if criteria is met. Like the LESS, higher scores indicate more movement pattern errors. To improve accuracy of the assessment, assessors are encouraged to use two video cameras to assess views from the frontal and sagittal plane. A study by Herrington et al (2013) found very good to excellent inter-tester reliability and excellent intra-tester reliability.[35] Evidence to support the ability to predict injury is currently lacking and a prospective study design would be beneficial in determining it's clinical usefulness.

Nordic Hamstring Test.

Hamstring activation and strength are important for proper co-activation of lower extremity muscles and improving dynamic stability of the knee. Additionally, hamstring activation can reduce strain on the ACL be opposing excessive anterior shear forces produced by the quadriceps.[31] The Nordic hamstring exercise is a lower extremity exercise used to target the hamstring group and has been very prominent in hamstring strain prevention programs.[49,50] Recently, the exercise has been proposed as a test for hamstring strength. Figure 6 shows the exercise and test. To perform the test, the subject assumes a kneeling position. While maintaining extension of the hips, the subject slowly lowers their body until he or she can no longer maintain a slow descent. The arms and hands are then used to buffer the fall.

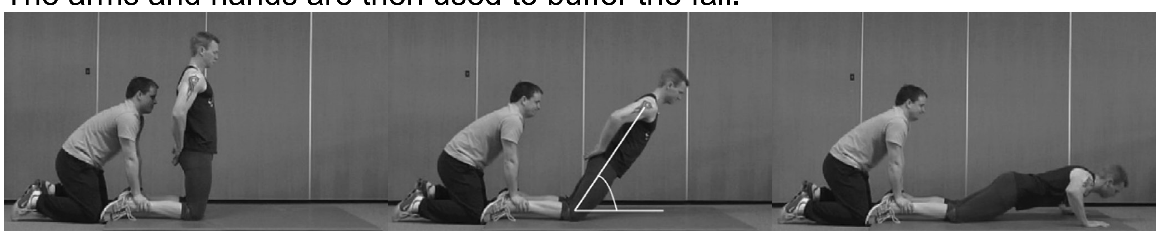


Figure 6. The Nordic Hamstring Test. ***From Sconce et al (2015).***[49]

In theory, a greater controlled range of motion achieved by an individual, the greater that individual's hamstring strength because the exercise gets progressively more challenging as the body leans forward. For the Nordic hamstring test, a video camera is used to record three repetitions. In the test, assessment of the "break point" is measured, which is the angle where a subject's hamstrings can no longer resist the gravitational moment and falls to the floor.[49] The angle was determined by lines created from the greater trochanter to lateral epicondyle and the horizontal. Sconce et al (2015) investigated the validity of the Nordic hamstring test and was able to demonstrate a strong relationship between the Nordic break-point angle and eccentric knee-flexor peak torque ($r = -0.808$, $r^2 = 65\%$).[49] Currently, there is no published data on the test's reliability and it has not been used as a screen for populations at risk of ACL injury. Opar et al (2013) created a device for the Nordic hamstring exercise that measures hamstring strength and symmetry with force transducers.[50] It could be used as a screening device, but special equipment is necessary limiting its practical use in the field at this time.

In conclusion, a number of tests have been provided, but none has enough empirical evidence to be considered a gold standard in ACL injury risk screening. Therefore, combinations of the tests mentioned may be useful in identifying generalized joint hypermobility, less than optimal movement patterns, and decreased strength.

Every clinical situation will vary, so clinical judgment will be required when selecting appropriate tests.

ACL Prevention Program Components

After identifying athletes with an increased risk of ACL injury, prevention programs have been proposed to help reduce this risk. There is mounting evidence that ACL prevention programs can reduce the risk of ACL injury. Pooled data in a meta-analysis by Sadoghi et al (2012) found risk reductions of 52% in female athletes and 85% in male athletes participating in various ACL prevention programs.[51] However, many of these programs exhibit significant heterogeneity in their design. Determining the most important components of a successful prevention program would allow for effective and efficient use of time for athletes, coaches, and practitioners. Based on a systematic review by Michaelidis et al (2014), multiple component prevention programs including plyometrics, dynamic stabilization, strength training for the trunk, upper and lower body, and sport specific agility training appear most beneficial.[52] Additionally, athlete education and feedback on proper technique appear critically important.[13,52–54] Sugimoto et al (2015) also investigated the effects of specific exercise components and found training programs incorporating plyometrics, strength training, and proximal control exercises to significantly reduce ACL injuries, while balance exercises did not appear to have an effect. As far as duration and frequency of training sessions, a meta-analysis by Sugimoto et al (2014) found multiple single sessions longer than 20 minutes that accumulate to more than 30 minutes per week were associated with greater reduction in injury risk during an in-season period.[55] Lastly, compliance with the prevention program is critically important. A systematic review by Sugimoto et al (2012) found significantly reduced ACL injury incidence in studies with high compliance rates (greater than 66% of sessions attended) compared to moderate and low compliance rates.[56] The data showed moderate compliance rates increased the risk of ACL injury by 3.1 times compared to high compliance rates. Also, low compliance rates increased the risk to 4.9 times compared to high compliance rates. This highlights the importance of not only designing a great program, but finding ways to motivate athletes to consistently participate in the program. Research regarding preventative programs is becoming more abundant and many programs are currently being developed. Improving prevention program methodology is key to helping our athletes remain healthy.

Conclusion

Preventing ACL injuries is not easy task. The complexity of risk factor identification, screening tests, and prevention programs are still being investigated. While research has moved sports medicine in the right direction, plenty of work still needs to be done in implementing this information into practice. As sports medicine practitioners, we can take this information back to our schools and clinics with hopes of making our sports safer.

References

1. Dohle S, Wansink B. Fit in 50 years: participation in high school sports best predicts one's physical activity after age 70. *BMC Public Health*. 2013;13:1100. doi:10.1186/1471-2458-13-1100.

2. Ardoy DN, Fernández-Rodríguez JM, Jiménez-Pavón D, Castillo R, Ruiz JR, Ortega FB. A Physical Education trial improves adolescents' cognitive performance and academic achievement: the EDUFIT study. *Scand J Med Sci Sports*. 2014;24(1):e52–61. doi:10.1111/sms.12093.

3. Swenson DM, Collins CL, Best TM, Flanigan DC, Fields SK, Comstock RD. Epidemiology of Knee Injuries among U.S. High School Athletes, 2005/2006-2010/2011. *Med Sci Sports Exerc*. 2013;45(3):462–469. doi:10.1249/MSS.0b013e318277acca.

4. Alentorn-Geli E, Myer GD, Silvers HJ, et al. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc*. 2009;17(7):705–29. doi:10.1007/s00167-009-0813-1.

5. Dai B, Herman D, Liu H, Garrett WE, Yu B. Prevention of ACL injury, part I: injury characteristics, risk factors, and loading mechanism. *Res Sports Med*. 2012;20(March 2015):180–97. doi:10.1080/15438627.2012.680990.

6. Ardern CL, Osterberg A, Tagesson S, Gauffin H, Webster KE, Kvist J. The impact of psychological readiness to return to sport and recreational activities after anterior cruciate ligament reconstruction. *Br J Sports Med*. 2014;48(22):1613–9. doi:10.1136/bjsports-2014-093842.

7. Ajuied A, Wong F, Smith C, et al. Anterior Cruciate Ligament Injury and Radiologic Progression of Knee Osteoarthritis: A Systematic Review and Meta-analysis. *Am J Sports Med*. 2013:1–11. doi:10.1177/0363546513508376.

8. Paterno M V, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of Second ACL Injuries 2 Years After Primary ACL Reconstruction and Return to Sport. *Am J Sports Med*. 2014;42(7):1567–1573. doi:10.1177/0363546514530088.

9. Mather RC, Koenig L, Kocher MS, et al. Societal and economic impact of anterior cruciate ligament tears. *J Bone Joint Surg Am*. 2013;95:1751–9. doi:10.2106/JBJS.L.01705.

10. Mall N a, Chalmers PN, Moric M, et al. Incidence and trends of anterior cruciate ligament reconstruction in the United States. *Am J Sports Med*. 2014;42(10):2363–70. doi:10.1177/0363546514542796.

11. LaBella CR, Hennrikus W, Hewett TE. Anterior Cruciate Ligament Injuries: Diagnosis, Treatment, and Prevention. *Pediatrics*. 2014;133(5):e1437–e1450. doi:10.1542/peds.2014-0623.

12. Noyes FR, Barber-Westin SD. Neuromuscular retraining intervention programs: do they reduce noncontact anterior cruciate ligament injury rates in adolescent female athletes? *Arthroscopy*. 2014;30(2):245–55. doi:10.1016/j.arthro.2013.10.009.

13. Acevedo RJ, Rivera-Vega A, Miranda G, Micheo W. Anterior cruciate ligament injury: identification of risk factors and prevention strategies. *Curr Sports Med Rep*. 2014;13(3):186–91. doi:10.1249/JSR.0000000000000053.

14. Hughes G, Watkins J. A risk-factor model for anterior cruciate ligament injury. *Sports Med*. 2006;36(5):411–28. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16646629.

15. Shultz SJ, Schmitz RJ, Benjaminse A, Chaudhari AM, Collins M, Padua D a. ACL Research Retreat VI: An update on ACL injury risk and prevention. *J Athl Train*. 2012;47(5):591–603. doi:10.4085/1062-6050-47.5.13.

16. Beynnon BD, Vacek PM, Newell MK, et al. The Effects of Level of Competition, Sport, and Sex on the Incidence of First-Time Noncontact Anterior Cruciate Ligament Injury. *Am J Sports Med*. 2014. doi:10.1177/0363546514540862.

17. Hewett TE, Zazulak BT, Myer GD. Effects of the menstrual cycle on anterior cruciate ligament injury risk: a systematic review. *Am J Sports Med*. 2007;35(4):659–668. doi:10.1177/0363546506295699.

18. Rahr-Wagner L, Thillemann TM, Mehnert F, Pedersen AB, Lind M. Is the use of oral contraceptives associated with operatively treated anterior cruciate ligament injury? A case-control study from the Danish Knee Ligament Reconstruction Registry. *Am J Sports Med*. 2014;42(12):2897–905. doi:10.1177/0363546514557240.

19. Fulton J, Wright K, Kelly M, et al. Injury risk is altered by previous injury: a systematic review of the literature and presentation of causative neuromuscular factors. *Int J Sports Phys Ther*. 2014;9(5):583–95. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=4196323&tool=pmcentrez&rendertype=abstract. Accessed December 16, 2014.

20. Smith HC, Vacek P, Johnson RJ, et al. Risk Factors for Anterior Cruciate Ligament Injury: A Review of the Literature -- Part 1: Neuromuscular and Anatomic Risk. *Sport Heal A Multidiscip Approach*. 2012;4(1):69–78. doi:10.1177/1941738111428281.

21. Uhorchak JM, Scoville CR, Williams GN, Arciero R a, St Pierre P, Taylor DC. Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. *Am J Sports Med*. 2003;31(6):831–842.

22. Myer GD, Ford KR, Paterno M V, Nick TG, Hewett TE. The effects of generalized joint laxity on risk of anterior cruciate ligament injury in young female athletes. *Am J Sports Med*. 2008;36(6):1073–1080. doi:10.1177/0363546507313572.

23. Vaishya R, Hasija R. Joint hypermobility and anterior cruciate ligament injury. *J Orthop Surg (Hong Kong)*. 2013;21(2):182–4. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24014780. Accessed April 7, 2015.

24. Junge T, Wedderkopp N, Thorlund JB, Søgaard K, Juul-Kristensen B. Altered knee joint neuromuscular control during landing from a jump in 10-15 year old children with Generalised Joint Hypermobility. A substudy of the CHAMPS-study Denmark. *J Electromyogr Kinesiol*. 2015. doi:10.1016/j.jelekin.2015.02.011.

25. Shultz SJ, Schmitz RJ, Cone JR, et al. Changes in Fatigue, Multiplanar Knee Laxity, and Landing Biomechanics During Intermittent Exercise. *J Athl Train*. 2015:150219105224004. doi:10.4085/1062-6050-49.5.08.

26. Hughes G. A review of recent perspectives on biomechanical risk factors associated with anterior cruciate ligament injury. *Res Sports Med*. 2014;22(March 2015):193–212. doi:10.1080/15438627.2014.881821.

27. Sugimoto D, Alentorn-Geli E, Mendiguchía J, Samuelsson K, Karlsson J, Myer GD. Biomechanical and Neuromuscular Characteristics of Male Athletes: Implications for the Development of Anterior Cruciate Ligament Injury Prevention Programs. *Sport Med*. 2015. doi:10.1007/s40279-015-0311-1.

28. Hewett TE, Myer GD, Ford KR, et al. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005;33(4):492–501. doi:10.1177/0363546504269591.

29. Lin C-F, Gross M, Ji C, et al. A stochastic biomechanical model for risk and risk factors of non-contact anterior cruciate ligament injuries. *J Biomech*. 2009;42(4):418–423. doi:10.1016/j.jbiomech.2008.12.005.

30. Hewett TE, Myer GD, Ford KR. Anterior cruciate ligament injuries in female athletes: Part 1, mechanisms and risk factors. *Am J Sports Med*. 2006;34(2):299–311. doi:10.1177/0363546505284183.

31. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train*. 2008;43(4):396–408. doi:10.4085/1062-6050-43.4.396.

32. Wild CY, Steele JR, Munro BJ. Insufficient hamstring strength compromises landing technique in adolescent girls. *Med Sci Sports Exerc*. 2013;45(3):497–505. doi:10.1249/MSS.0b013e31827772f6.

33. Iguchi J, Tateuchi H, Taniguchi M, Ichihashi N. The effect of sex and fatigue on lower limb kinematics, kinetics, and muscle activity during unanticipated side-step cutting. *Knee Surgery, Sport Traumatol Arthrosc*. 2014;22(1):41–48. doi:10.1007/s00167-013-2526-8.

34. Swart E, Redler L, Fabricant PD, Mandelbaum BR, Ahmad CS, Wang YC. Prevention and screening programs for anterior cruciate ligament injuries in young athletes: a cost-effectiveness analysis. *J Bone Joint Surg Am*. 2014;96(9):705–11. doi:10.2106/JBJS.M.00560.

35. Herrington L, Myer GD, Munro A. Intra and inter-tester reliability of the tuck jump assessment. *Phys Ther Sport*. 2013;14(3):152–155. doi:10.1016/j.ptsp.2012.05.005.

36. Dallinga JM, Benjaminse A, Lemmink K a PM. Which screening tools can predict injury to the lower extremities in team sports?: a systematic review. *Sports Med*. 2012;42(9):791–815. doi:10.2165/11632730-000000000-00000.

37. Boyle KL, Witt P, Riegger-Krugh C. Intrarater and Interrater Reliability of the Beighton and Horan Joint Mobility Index. *J Athl Train*. 2003;38(4):281–285. Available at: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=314385&tool=pmcentrez&rendertype=abstract. Accessed April 11, 2015.

38. Naal FD, Hatzung G, Müller A, Impellizzeri F, Leunig M. Validation of a self-reported Beighton score to assess hypermobility in patients with femoroacetabular impingement. *Int Orthop*. 2014;38(11):2245–50. doi:10.1007/s00264-014-2424-9.

39. Juul-Kristensen B, Hansen H, Simonsen EB, et al. Knee function in 10-year-old children and adults with Generalised Joint Hypermobility. *Knee*. 2012;19(6):773–778. doi:10.1016/j.knee.2012.02.002.

40. Cook G. *Movement*. Santa Cruz, CA: On Target Publications; 2011.

41. McCall A, Carling C, Nedelec M, et al. Risk factors, testing and preventative strategies for non-contact injuries in professional football: current perceptions and practices of 44 teams from various premier leagues. *Br J Sports Med*. 2014;48(18):1352–7. doi:10.1136/bjsports-2014-093439.

42. McCall a., Carling C, Davison M, et al. Injury risk factors, screening tests and preventative strategies: a systematic review of the evidence that underpins the

perceptions and practices of 44 football (soccer) teams from various premier leagues. *Br J Sports Med*. 2015:1–8. doi:10.1136/bjsports-2014-094104.

43. Zalai D, Panics G, Bobak P, Csáki I, Hamar P. Quality of functional movement patterns and injury examination in elite-level male professional football players. *Acta Physiol Hung*. 2014;1(-1):1–9. doi:10.1556/APhysiol.101.2014.010.

44. Letafatkar A, Hadadnezhad M, Shojaedin S. RELATIONSHIP BETWEEN FUNCTIONAL MOVEMENT SCREENING SCORE AND HISTORY OF INJURY. *Int J Sports Phys Ther*. 2014;9(1):21–27.

45. Padua D a., DiStefano LJ, Beutler AI, de la Motte SJ, DiStefano MJ, Marshall SW. The Landing Error Scoring System as a Screening Tool for an Anterior Cruciate Ligament Injury–Prevention Program in Elite-Youth Soccer Athletes. *J Athl Train*. 2015;50(1):150326115639000. doi:10.4085/1062-6050-50.1.10.

46. Padua D a, Marshall SW, Boling MC, Thigpen C a, Garrett WE, Beutler AI. The Landing Error Scoring System (LESS) Is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *Am J Sports Med*. 2009;37(10):1996–2002. doi:10.1177/0363546509343200.

47. Smith HC, Johnson RJ, Shultz SJ, et al. A prospective evaluation of the Landing Error Scoring System (LESS) as a screening tool for anterior cruciate ligament injury risk. *Am J Sports Med*. 2012;40(3):521–6. doi:10.1177/0363546511429776.

48. Myer GD, Ford KR, Hewett TE. Tuck Jump Assessment for Reducing Anterior Cruciate Ligament Injury Risk. *Athl Ther Today*. 2008;13(5):39–44. doi:10.1055/s-0029-1237430.Imprinting.

49. Sconce, E. Jones P. The validity of the Nordic hamstring lower as a field-based assessment of eccentric hamstring strength. *J Sport Rehabil*. 2015;24(1):13–20.

50. Opar D a, Piatkowski T, Williams MD, Shield AJ. A Novel Device Using the Nordic Hamstring Exercise to Assess Eccentric Knee Flexors Strength: A Reliability and Retrospective Injury Study. *J Orthop Sports Phys Ther*. 2013;43(9):636–640. doi:10.2519/jospt.2013.4837.

51. Sadoghi P, von Keudell A, Vavken P. Effectiveness of anterior cruciate ligament injury prevention training programs. *J Bone Joint Surg Am*. 2012;94(9):769–76. doi:10.2106/JBJS.K.00467.

52. Michaelidis M, Koumantakis G a. Effects of knee injury primary prevention programs on anterior cruciate ligament injury rates in female athletes in different sports: A systematic review. *Phys Ther Sport*. 2013;15(3):200–210. doi:10.1016/j.ptsp.2013.12.002.

53. Gokeler A, Benjaminse A, Hewett TE, et al. Feedback techniques to target functional deficits following anterior cruciate ligament reconstruction: implications for motor control and reduction of second injury risk. *Sports Med*. 2013;43(11):1065–74. doi:10.1007/s40279-013-0095-0.

54. Benjaminse A, Gokeler A, Dowling A V., et al. Optimization of the Anterior Cruciate Ligament Injury Prevention Paradigm: Novel Feedback Techniques to Enhance Motor Learning and Reduce Injury Risk. *J Orthop Sport Phys Ther*. 2015;45(3):170–182. doi:10.2519/jospt.2015.4986.

55. Sugimoto D, Myer GD, Barber Foss KD, Hewett TE. Dosage effects of neuromuscular training intervention to reduce anterior cruciate ligament injuries in female athletes: meta- and sub-group analyses. *Sports Med*. 2014;44(4):551–62. doi:10.1007/s40279-013-0135-9.

56. Sugimoto D, Myer GD, Bush HM, Klugman MF, Medina McKeon JM, Hewett TE. Compliance with neuromuscular training and anterior cruciate ligament injury risk reduction in female athletes: a meta-analysis. *J Athl Train*. 47(6):714–23. doi:10.4085/1062-6050-47.6.10.