Review Article

Hip and trunk muscle dysfunction: implications for anterior cruciate ligament injury prevention

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Abstract: Due to the short and long-term consequences of anterior cruciate ligament (ACL) injury, significant efforts have been devoted to identifying injury risk factors and develop screening and prevention tools. A growing body of evidence has identified hip and trunk muscle strength and functional performance as modifiable risk factors in ACL injury. Screening tools have been developed to capture hip and trunk function in order to identify athletes with elevated injury risk. Furthermore, ACL injury prevention programs include activities to improve hip and trunk strength and motor control during dynamic tasks. Because of the considerable focus and the growing body of evidence, the role of the hip and trunk in ACL injury etiology, screening tools, and prevention programs requires review and synthesis for improved implementation in clinical practice. Thus, the purpose of this review is to highlight the role of the hip and trunk in primary ACL injury, identify screening tests that may reveal deficits of the hip and trunk, and discuss the efficacy of prevention programs in correcting hip and trunk risk factors and ACL injury risk.

Keywords: Anterior cruciate ligament (ACL); prevention; hip; trunk

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Introduction: the anterior cruciate ligament (ACL) injury epidemic

Approximately seven million people each year receive medical care for sports-related injuries, including sprains, strains, and fractures (1). The knee is the second most frequently injured joint in the body, behind only the ankle, with the ACL being the most commonly injured knee ligament (1,2). Of the up to 200,000 annual ACL injuries in the United States, females tear their ACL at a four to five times higher rates than their male counterparts competing in the same sport and level of competition (3,4). ACL injury risk is due to extrinsic and intrinsic risk factors such as ligament laxity, boney morphology, training techniques, muscle weakness and poor neuromuscular control (3,5). Extrinsic factors are readily modifiable and have thus been the focus of screening and prevention programs.

Due to the negative sequelae of ACL injury, primary prevention is important to limit the first-time injury rate and avoid the short and long-term consequences of injury. Muscle weakness and compensatory movement patterns associated with the injury contribute to abnormal knee loading in daily activities such as walking and running (6-8). Weakness and movement compensations contribute to poor short-term outcomes including the inability to return to prior level of function and increased risk of subsequent injuries to the contralateral or ipsilateral side (9,10). In the long term, the consequences of ACL injury continue to manifest with approximately 50% of individuals developing knee osteoarthritis and 70% reporting pain and limited knee function within 10–20 years after reconstructive surgery (10). These high rates of first-time ACL injuries coupled with long-term and persistent negative consequences of injury highlight the need for injury prevention programs and screening tools. Thus, the purpose of this review is to highlight the role of the hip and trunk in primary ACL injury, identify screening tests that may reveal deficits of the hip and trunk, and discuss the efficacy of prevention programs in correcting hip and trunk risk factors and ACL injury risk.

The role of the trunk and hip in ACL injury

Mechanics of the trunk, hip, and knee have been identified as key factors in noncontact ACL injury etiology (11). As the trunk accounts for approximately 50 percent of an individual's overall body mass, even small deviations in its position could have a significant impact on hip and knee muscular demand and on forces across the knee joint (12). Additionally, the hip can be influenced by the trunk, and has been identified as the proximal origin to many abnormal knee motions associated with ACL injury risk. In the sagittal plane, a more vertical trunk position and a center of mass positioned posterior to the base of support are associated with increased knee extensor moment and noncontact ACL injury, respectively (13,14). In the frontal plane, increased lateral trunk displacement is positively correlated with knee abduction moment, a strong risk factor for ACL injury (15). In multi-plane tasks such as cutting, excessive trunk flexion and limited trunk rotation towards the direction of the cut have been associated with elevated hip and knee internal rotation moments (16). The consistent relationship between suboptimal trunk position and increased hip and knee-related ACL injury risk factors highlights the influence of trunk position in ACL injury. Furthermore, hip collapse resulting in hip adduction and internal rotation can place the limb in "dynamic valgus" (17,18) and increased frontal plane hip motions are correlated with increased knee abduction load (19). Preventing dynamic valgus is primarily performed by the activation of the hip abductors and hip external rotators. As such, preseason strength values for hip abduction and hip external rotation independently predicted ACL injury in competitive athletes (20) and strength measures in hip extension, abduction, and external rotation have been negatively correlated with knee valgus angle in females (21). The effects of trunk and hip muscle performance may manifest uniquely in females compared to males suggesting sex-specific mechanisms involved in increased ACL injury risk. In a single prospective study, lateral trunk displacement after perturbation was a strong predictor of ACL injury with 91% sensitivity and 68% specificity in female, but not male athletes (22). Additionally, trunk proprioception, as measured via active and passive repositioning, was identified as a predictor of ACL injury in females (23). Subjects with better core stability test performance demonstrated better dynamic postural stability, indicating that improving core stability in females may improve dynamic trunk motion during athletic tasks (24). Similar to the trunk, there appear to be some sex-specific factors as only hip extension strength but not hip abduction or external rotation strength was correlated with greater knee flexion motion during landing tasks and subsequent reduction in ACL injury risk in males (21). These aggregate findings highlight abnormal motor control and dynamic performance of the trunk and hip as modifiable factors that may be addressed to reduce ACL injury risk.

When synthesized with cadaveric and modeling studies investigating ACL strain, the findings of the previously discussed in-vivo studies further suggest a critical role of the trunk and hip in ACL injury. Multiple studies have demonstrated that anterior tibial shear increases ACL strain (25-27). As a surrogate measure of force across the knee joint, the knee extensor moment provides information on the amount of potential anterior translation occurring during dynamic activities from quadriceps force. Landing with a more erect trunk is noted to result in a greater knee extensor moment and a more posterior center of mass, both measures linked with an increase in ACL strain (14). Furthermore, models of ACL strains have identified that knee valgus moment combined with anterior shear and knee rotation moments resulted in the greatest ACL strain than any of the three in isolation (25,28). As noted previously, poor hip and trunk position and muscle performance result in increased knee abduction moment, knee internal rotation moment, and dynamic valgus, suggesting a clear linkage between trunk and hip position and ACL strain.

The combination of the previously discussed evidence suggests that both trunk and hip dynamic performance are important contributors to noncontact ACL injury risk and should be considered in any ACL screening or prevention program. Identifying abnormal trunk or hip position, impaired strength, or impaired dynamic trunk performance using evidence-based screening tools may assist coaches and clinicians in identifying those with elevated ACL injury risk factors. Early identification may assist in guiding the athletes to participate in prevention programs before an ACL injury occurs. The subsequent section discusses the current evidence for screening tests of ACL injury risk with emphasis on tests that account for hip or trunk motor control or muscle strength.

Screening tests for ACL injury risk

While a multitude of screening tools for ACL injury risk have been developed, few have been prospectively tested. Two methods that have been prospectively assessed for ACL injury risk: landing error scoring system (LESS) and hip strength assessment. Both methods include an assessment of either hip or trunk motor control or muscle strength and are discussed in the context of currently available evidence for ACL injury screening tools.

LESS

The LESS assesses an individual's jump landing technique through video analysis of a bilateral drop vertical jump task. Two cameras, each placed 3.54 m from the landing area are utilized: one to assess sagittal plane motion and the second to assess frontal plane motion. The individual performs 3 trials of a drop vertical jump from a 30-cm box to a horizontal distance 50% of their standing height away from the box (29). The individual is scored on 17 items with each item representing a potential movement error. The total score is summed with a higher score indicating poorer landing technique. Ten of the 17 items address trunk and lower extremity position at initial contact and maximum knee angle. An additional 5 items address foot position at various time points and the final two items assess overall sagittal plane motion and the rater's general perception of landing quality. An item is considered an error if the faulty motion is identified on 2 of the 3 landing trials. The LESS has demonstrated moderate to excellent intrarater reliability and excellent novice *vs.* expert user interrater reliability (29).

To date, two prospective studies have evaluated LESS score and noncontact ACL injury risk. The earliest study found the LESS score was not predictive of ACL injury in high school and collegiate athletes from a multitude of sports (30). Conversely, a later study in elite youth soccer players identified a LESS score of 5 as the appropriate cutoff value for increase ACL injury risk with a sensitivity of 86% and a specificity of 64% (31). The authors noted differences in age, physical maturity, type of sport played, and differences in inclusion and exclusion criteria of the two studies may have accounted for the conflicting results (31). Thus, the LESS is shown to be correlated with measures of ACL loading and ACL injury biomechanics, however, the current evidence suggests additional prospective studies are needed across age and sport profiles to further test the predictive properties of the LESS as it relates to ACL injury risk.

Isometric hip strength

A single prospective study assessed hip abduction and hip external rotation peak isometric strength and ACL injury in male and female athletes (20). Strength measures were recorded using a handheld dynamometer and stabilization strap, making this screening tool easily implemented in clinic or sport settings due to low equipment demands. When assessed during preseason, hip external rotation and abduction strength independently predicted noncontact ACL injury during the season with 93% sensitivity, 59% specificity and 87% sensitivity, 65% specificity, respectively (20). Cutoff values of ≤20.3 percentage of bodyweight for hip external rotation and ≤35.4 percentage of bodyweight for hip abduction were identified and sex did not significantly influence the observed relationships (20). This study suggests that the cutoff values for peak isometric hip abduction and hip external rotation strength may be of value in preseason screening for ACL injury risk. However, it should be noted that the cutoff values developed from this study have not been prospectively evaluated nor have the findings of this initial study been replicated.

Other screening tools such as the tuck jump assessment, hip rotation passive range of motion, quadriceps and hamstring muscle strength have been associated with factors related to ACL injury risk, but have not been prospectively assessed. Although they have yet to be assessed prospectively, it is worth reviewing the methodology for each screen and the current best evidence for their use.

Tuck Jump

The Tuck Jump involves ten criteria that are visually evaluated in either real-time or with photos/video to assess the individuals jump landing mechanics (32). The athlete is asked to jump vertically and bring their knees to their chest and repeat the task for 10 s. A score of one is given for each criteria if a faulty movement is identified such that a score of 0 indicates optimal landing technique and a score of 10 indicates poor technique. Criteria specific to the hip and trunk include lower extremity valgus during landing (hip adduction/internal rotation), asymmetrical thighs during flight and at the peak of the jump, and a decline in jumping technique during the course of the test. The Tuck Jump assessment has demonstrated very good to excellent intra- and interrater reliability (33). However, the predictive ability of the Tuck Jump assessment to biomechanical risk factors of ACL injury or incidence of ACL injury has yet to be established.

Hip rotation passive range of motion

A recent study identified males and females shortly after ACL injury as having less hip rotation excursion and peak passive hip internal rotation angle than those without an ACL injury (34). Using a logistic regression, the authors determined the odds of having an ACL injury decreased by 0.419 with every 10 degree increase in hip IR passive range of motion (34). A previous study noted similar findings of increased hip rotation range of motion in soccer players without ACL injury compared to those with an ACL injury (35). A strong association was observed between limited hip range of motion and increased incidence of ACL injury, mainly due to limited hip internal rotation motion (35). It is hypothesized that limited hip rotation motion may increase ACL injury risk due to the knee incurring greater rotational motion and loading as a result of reduced available motion in the hip joint. These preliminary studies indicate that hip rotation range of motion may be a useful screening tool, but continued work is needed to verify the previous findings and identify the predictive properties of this method.

Quadriceps and hamstring strength

Although the focus of this review is on the role of the hip and trunk in ACL injury risk, quadriceps and hamstring strength are considered modifiable risk factors that serve to provide additional dynamic stability to the knee joint. Unfortunately, current evidence does not support peak quadriceps strength or hamstring strength measures as screens for ACL injury risk. A four year prospective study of military cadets found no effect of eccentric or concentric quadriceps or hamstring strength in those with ACL injury (36). A separate matched case-control study utilizing multivariate analysis found no association between quadriceps and hamstring strength to ACL injury in high school and collegiate athletes (37). More recently, Steffen *et al.* found no association of peak concentric quadriceps or hamstring strength with noncontact ACL injury in elite female handball players (38). The lack of relationship between quadriceps and hamstring strength and ACL injury suggests that proximal factors including the hip and trunk may be more influential in ACL injury risk.

In utilizing the screening tools discussed above, coaches and clinicians are better equipped to identify athletes at increased risk for ACL injury. Upon identification, these high-risk athletes can initiate prevention programs aimed at addressing muscle strength and movement impairments identified from the screening tests. The next section of this review will discuss the effectiveness, mode of implementation, and limitations of current ACL injury prevention programs.

Prevention programs

ACL prevention programs have focused on targeting the impairments associated with initial ACL injuries such as strength and neuromuscular control. Among the first programs to integrate risk factor reduction were Caraffa *et al.* in 1996 and Hewett *et al.* in 1999 (39,40). Hewett's program focused on flexibility, plyometric control, and strength while Caraffa's program focused on lower extremity balance with both protocols progressively increasing in difficulty as lower level tasks were mastered. Both found a significant decrease in ACL injuries seasons following the training. Since these early programs found a significant decrease in injury rates with trunk and lower extremity training, future programs have attempted to develop protocols which can be administered by non-medical personnel, and can be safely and easily performed throughout an athletic season. The two most studied prevention programs are the FIFA 11+ and variations of neuromuscular training programs which integrate strength and balance training.

FIFA 11+

The FIFA 11+ program was created in the early 2000's to reduce knee injuries in young soccer athletes (41). It can be performed on the field before practices and games and has a low equipment demand, making the program attractive to coaches and athletic programs. The FIFA 11+ consists of a dynamic warm-up coupled with strengthening, balancing, and plyometric tasks, targeting control and strength of the trunk and lower extremities. The set-up comprises two lanes of 6 parallel cones with 5–6 m between each cone. The athletes start with six dynamic running activities involving forward, retro, and lateral movements. They then are paired with a teammate to complete six trunk stability, balance, and strengthening activities such as bridges, single leg balance, and lateral hopping. Exercises can be progressed or regressed within three available levels of each task. The FIFA 11+ is then completed with three more running and cutting tasks, increasing intensity as the athlete prepares for their sporting endeavors.

The FIFA 11+ has significantly decreased lower extremity injury rates in both soccer and basketball athletes (42,43) within the season the intervention was provided. Activation patterns of the hamstrings and foot and ankle musculature improved with four weeks of the FIFA 11+'s strengthening and trunk stability exercises (44). Therefore, pre-season conditioning should include the FIFA 11+ with continuation of the program throughout the season (44). Recent systematic reviews concluded that the FIFA 11+ is effective at decreasing all lower extremity injuries, especially ACL injuries, and improving dynamic balance and agility for soccer athletes (45). It should be noted, however, that the benefits of the training do not extend past the year the intervention was provided, so to derive maximum benefit and injury risk reduction, FIFA 11+ training must become part of the athlete's regular training regime (45,46). Due to the low cost of implementation and the improvements in balance and agility, the FIFA 11+ is a cost-efficient method to decrease injury rates and improve performance in soccer and basketball athletes.

Neuromuscular training

Prevention programs involving neuromuscular training often include elements of balance, plyometric training, and strengthening with the specific activities varying between study protocols. Systematic reviews and meta-analyses of all neuromuscular training studies have consistently concluded that no significant difference is found between groups participating in training and controls (47,48). However, Sugimoto *et al.* assessed specific subgroups of training, and found successful training programs consistently integrated multiple elements into training without targeting only a single impairment such as strength or balance (48). In Sugimoto *et al.*'s subgroup analysis, many studies included single leg balance with perturbations for balancing training while others utilize balancing equipment such as a balance board. Plyometric and neuromuscular control tasks included single leg hopping, squat jumps, jumps with a turn, bounding, and run and plant tasks. Lower extremity strengthening included squats, leg press, calf raises, abdominal curls, back extensions, and planks. Strengthening and proximal control programs displayed the greatest benefit while balance and plyometric exercises did not significantly decrease the rate of ACL injuries (48). Therefore, for neuromuscular prevention programs to be successful, hip and trunk strength and control are critical.

Like the FIFA 11+, neuromuscular training is best to initiate either before puberty or early in puberty and continue throughout an athlete's sporting career. Myer *et al.* conducted a meta-analysis in 2013, assessing the influence of age on neuromuscular training prevention programs (49). For individuals at high risk for an ACL injury, greatest changes were seen in younger athletes, specifically under the age of 18 with benefits observed in athletes as young as 7 years old. Hewett recently published a meta-analysis of his neuromuscular training program and recommends starting prevention programs before or early in puberty (5). By addressing strength deficits and faulty trunk and hip control before the individual begins the growth spurt associated with puberty, neuromuscular control can be reinforced with small corrections throughout puberty as opposed to attempting large corrections during a rapidly changing neuromusculoskeletal system.

Prevention programs an ACL injury: a dose-response relationship

Preventions programs such as the FIFA 11+ and neuromuscular training are best initiated when athletes are under the age of 18 and can be initiated when athletes are as young as 7 (5,41). While it is safe to weight train with young athletes, proper form is critical to reinforce in this population (5). Most prospective studies of the FIFA 11+ and neuromuscular training programs only assess injury rates over a single season. However, when athletes participate in the program more frequently, the risk of injury continues to decrease (5,46). Therefore, to maintain a low risk of injury, it is recommended to initiate the training while athletes are young and to continue the training throughout their athletic career.

Screening and targeted prevention vs. prevention for all

An initial study of the cost-effectiveness of prevention programs for all versus targeted prevention of only high risk athletes via screening tools revealed inclusion of all athletes was the most cost-effective strategy (50). The study's findings were primarily driven by the ease and relatively low cost of having entire teams participating in prevention programs. This outweighs the time burden of screening to identify the high-risk athletes. The authors note that as screening tools improve in both efficiency and accuracy, the cost-effectiveness is likely to improve. However, due to athletes' busy schedules and the demand of coaches to focus on sport-specific drills, team training may not be available. If a team cannot train together, screening tools may be more useful in identifying athletes who should seek additional training outside of the team environment.

Conclusions

Trunk and hip muscle performance and motor control are significant contributors to ACL injury risk. Although the currently existing screening tests are increasingly able to discriminate between high and low risk athletes, concerns regarding cost-effectiveness often limit large-scale implementation of screening assessments. Prevention programs featuring progressive hip and trunk muscle strengthening exercises, balance, and neuromuscular re-education activities decrease the risk of ACL injury, but a strong dose-response relationship requires ongoing participation for maximum injury risk reduction.

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