The Mechanistic Connection Between the Trunk, Hip, Knee, and Anterior Cruciate Ligament Injury

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HEWETT, T.E. and G.D. MYER. The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exerc. Sport Sci. Rev.*, Vol. 39, No. 4, pp. 161–166, 2011. *Neuromuscular control of the trunk and knee predicts anterior cruciate ligament injury risk with high sensitivity and specificity. These predictors are linked, as lateral trunk positioning creates high knee abduction torque (load). The hypotheses explored are that lateral trunk motion increases load and that neuromuscular training that enhance trunk control will decrease load.* **Key Words:** knee injury, high risk biomechanics, ACL injury prevention, neuromuscular control, female sports injuries, identification of knee injury risk factors

INTRODUCTION: THE MECHANISTIC CONNECTION BETWEEN THE TRUNK AND THE KNEE

The goal of this *Perspective for Progress* is to lead to advances in the understanding of the mechanisms and prevention of anterior cruciate ligament (ACL) injuries in female athletes, who are at a 2- to 10-fold greater risk of ACL injury than male athletes. The overall scientific objectives are to determine the mechanisms by which female athletes become more susceptible to ACL injury and to optimize the effectiveness of interventions designed to prevent ACL injuries. Specifically, this perspective is directed toward understanding and exploring the following questions: 1) Does decreased neuromuscular control of the trunk (*i.e.*, active stabilization of lateral trunk motion) underlie increased loading of the knee joint in female athletes? 2) Does this increased loading occur through both biomechanical (ΔGRFv driven—the change in frontal plane position of the ground reaction force vector) and neuromuscular (hip adductor driven) mechanisms? 3) Does neuromuscular training (*i.e.*, training focused to increase active stabilization and control during dynamic movements) of the trunk decrease abduction load at the knee?

Analysis of neuromuscular control of the trunk may be a useful new perspective for the determination of the mechanisms underlying increased risk for ACL injury and for the optimization of risk screening and intervention programs. The preponderance of prior research has focused on the resultant symptoms, knee motions, and loads, as risk factors, as opposed to the potential underlying root of the problem, neuromuscular control of the trunk. The causes of risky knee loads and motions are not likely in the knee, rather it is probable that high-risk knee loads are the resultant symptoms to reduced control of body posture and trunk accelerations. A narrow perspective, which focuses on knee motions and loads may lead not only to the misinterpretation of underlying injury mechanism, but it may prohibit the application of optimal intervention, as the determination of knee load levels cannot be incorporated readily into clinic or field-based screening programs and can be difficult to communicate to athletes. The valgus moment at the knee is not visible, and the relevant differences in the valgus angle are in the range of five to six degrees, which hardly is quantifiable by the naked eye. However, relative trunk control, or increased trunk motion, is not only a likely major underlying factor; it is more visible and can be explained readily to athletes and athletic trainers (Figs. 1 and 2). Hence, examination of neuromuscular

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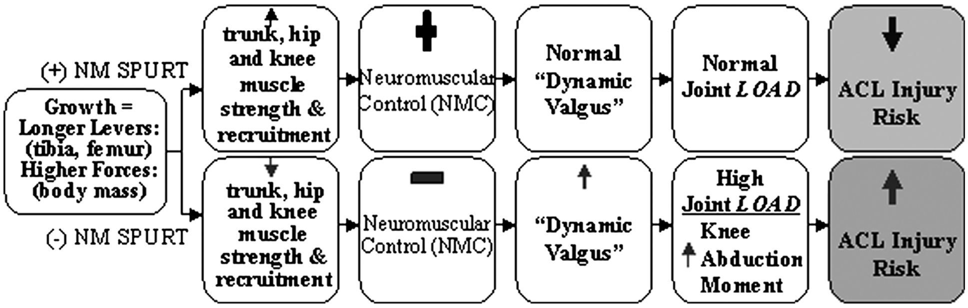

Figure 1. Theory linking growth, neuromuscular (NM) adaptation, trunk NMC, "dynamic valgus," and knee joint load to anterior cruciate ligament (ACL) injury risk (14,46).

control of the trunk results in measurable variables that likely are closer to the higher level control mechanisms.

A series of studies have developed the logical basis behind the hypotheses delineated above. 1) We (27) demonstrated that the mechanism of noncontact ACL injuries in female athletes, as observed on video, includes lateral trunk motion with the body shifted over one leg, which was associated with high knee abduction or medial knee collapse (30,32,48). Lateral perturbation of the trunk is another common component of the mechanism (5,32). Hence, increased lateral sway of the trunk may underlie medial collapse of the knee joint in female athletes. 2) Zazulak *et al.* (56) demonstrated that trunk displacement and coronal plane knee load both predict ACL injury risk in female athletes with high sensitivity and specificity and accuracy (91%) (20). Therefore, increased knee loading occurs through both neuromuscular and biomechanical mechanisms related to increased trunk inertia and motion. 3) Finally, both initial (25) and confirmatory investigation (45,50) have demonstrated that neuromuscular control of the trunk and lower extremity can be improved with neuromuscular training. Neuromuscular control of the trunk has the potential to decrease abduction load at the knee and to decrease ACL injury risk (17,40–42,45). With these concepts in mind, we will focus the remainder of the "Perspectives for Progress" review on the scientific justification (*e.g.*, trunk and knee are coupled mechanically and dynamically via the ground reaction force (GRF) lever arm) and the evidence of a correlation from movement analysis studies (Fig. 2).

Prophylactic intervention for ACL injury could prevent a significant percentage of the 100,000 to 250,000 injuries that occur each year in the United States (17,53). The President's council on physical fitness recommends that women, both young and old, remain active to maintain optimal health. Reduction of female injury rates from five times to equal male athletes' potentially would allow female athletes annually to continue the health benefits of sports participation and avoid the long-term complications of osteoarthritis, which occurs with a 10- to 100-fold greater incidence in ACL-injured than in uninjured athletes (34).

ACL Injury Rate Differences and Long-Term Sequelae in Female Athletes

Adolescent and mature female athletes who participate in pivoting and jumping sports experience ACL injuries at a

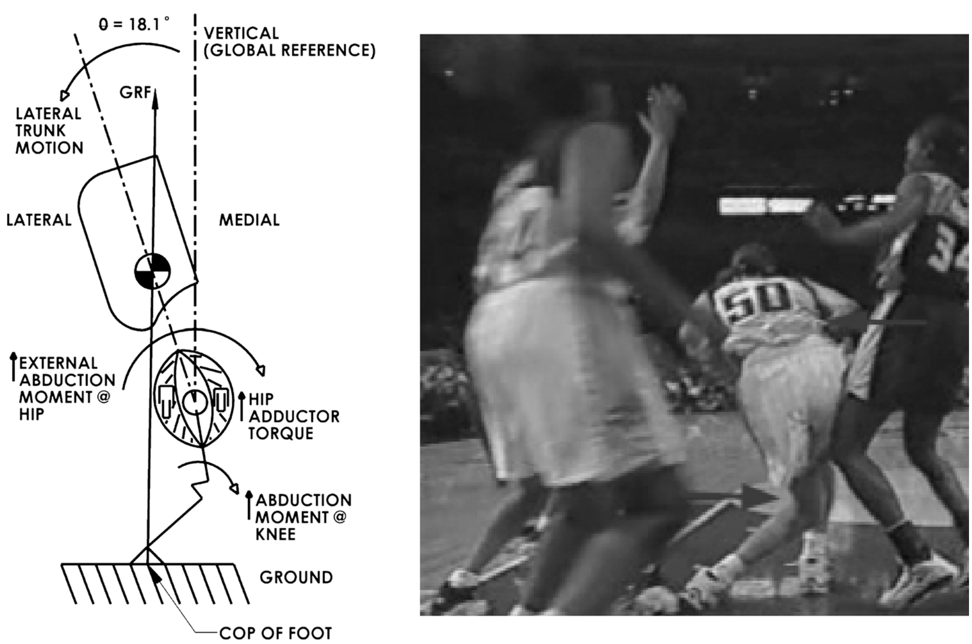

Figure 2. Mechanical model linking 1) lateral trunk motion to change in direction of the ground reaction force vector (ΔGRFv), 2) hip adductor torque, and 3) knee load during cutting and landing anterior cruciate ligament (ACL) injuries.

2- to 10-fold greater rate than male athletes participating in the same high-risk cutting and landing sports (1). The combination of this greater susceptibility and a 10-fold increase in the female sports population since the inception (June 23, 1972) of Title IX has resulted in a dramatic increase in the number of ACL injuries in female athletes. In the United States, 100,000–250,000 ACL injuries occur each year (17). The associated costs may exceed $650 million annually in female varsity athletics alone (19). Neuromuscular control deficits at the hip and trunk may follow maturation (Fig. 1) and may contribute to decreased active neuromuscular control of the lower extremity that may lead to increased knee abduction loads and strain on the knee ligaments (3,18,20,37). The costs associated with ACL injury do not end with the ACL reconstruction and rehabilitation. There is a strong association between ACL injury and development of posttraumatic knee osteoarthritis at a relatively young age, which also occurs with much greater incidence in female athletes than male athletes (34). It is estimated that between 50% and 100% of women with an ACL injury will show significant pain, functional limitations, and radiographic signs of knee osteoarthritis within 12–20 yr of the index injury (34). Prediction of who is at risk and how and when their risk increases has potential to prevent unnecessary injury, have them maintain desirable physical activity and fitness level throughout their lifespan, and to significantly improve outcomes after injury.

Coronal Plane Components of the ACL Injury Mechanism in Female Athletes

Trunk displacement and coronal plane knee load both predict ACL injury risk in female athletes. Specifically, knee abduction loads and neuromuscular control of the trunk both predict ACL injury risk with high sensitivity and specificity. Knee abduction load predicted ACL injury risk with 78% sensitivity and 73% specificity (20). A logistic regression model that incorporated lateral trunk motion predicted ACL injury risk in female athletes with 83% sensitivity and 76% specificity but did not predict either general knee or specifically ACL injury risk in male athletes (56). The mechanism of ACL injury may differ in female and male athletes, especially with respect to the dynamic positioning of the knee, as female athletes demonstrate greater valgus collapse of the lower extremity primarily in the coronal plane (32). Most ACL injuries in female athletes occur by noncontact mechanisms during landing and lateral pivoting (48). The mechanism of noncontact ACL injuries as observed on video has several common components in female athletes: high knee abduction, lateral trunk motion with the body shifted over one leg and the plantar surface of the foot fixed flat on the playing surface, displaced away from the trunk and low knee flexion (30,32,48). Unanticipated perturbation of the trunk is another common component of the mechanism (5,32).

Trunk motion can influence knee abduction load through mechanical and neuromuscular mechanisms (Figs. 1 and 2) (22). For example, if the trunk moves laterally (relative to the stance limb), the GRF vector (GRFv) may move laterally and have a greater lever arm relative to the knee joint center. This directly will increase the potential for knee abduction loading in combination with increased inertial acceleration of the trunk or thigh segments during dynamic movement. The resultant knee load simultaneously increases in magnitude of GRFv because of unicompartmental (*i.e.*, lateral compartment loads from knee abduction stance) knee joint loading (22,43). In response to the lateral trunk motion and increased knee load, it is essential to counteract with increasing reactive hip adductor torque to maintain upright stance and dissipate lower extremity forces. Increased hip adductor torque can increase knee abduction moments, which are predictors of peak GRF (25) and an important determinant of joint load. Knee abduction torque places knee ligaments in the high slope (load) segment of their force-length curve and elicits knee pain in female athletes (52). Video evidence of ACL injuries shows that the female trunk usually moves laterally toward the ACL injured limb as the knee abducts (Fig. 2) (26).Ultimately, when the trunk leans to one side, the hip adductors are activated to right the pelvis and trunk to maintain stance; however, this strategy of movement, during dynamic high-load scenarios seems to initiate a viscous mechanical cycle, which underlies the inciting mechanism of knee (ACL and patellofemoral pain disorder) injury in female sports.

Mechanical Mechanisms Related to Lateral Trunk Motion and Knee Load in Female Athletes

Trunk position and knee external abduction moment (load) may be linked mechanically, as lateral positioning of the trunk can create abduction loads at the knee (Figs. 2 and 3) (54). In the coronal plane, applying static equilibrium mechanics and neglecting the inertia of the body segments between hip and ground, if the GRF passes lateral to the center of the head of the femur, an external hip abduction torque results (54). This external moment is balanced by a hip adductor generated torque of equal magnitude. There is a strong association (r = 0.62–0.77) between lateral trunk lean and both hip adductor torque and coronal plane knee valgus stress during pathological gait (13,49). Interestingly, even alteration of arm position relative to the centerline of the body can increase the external knee abduction load by 29%–60% (13,49). At the low knee flexion angles that are present during

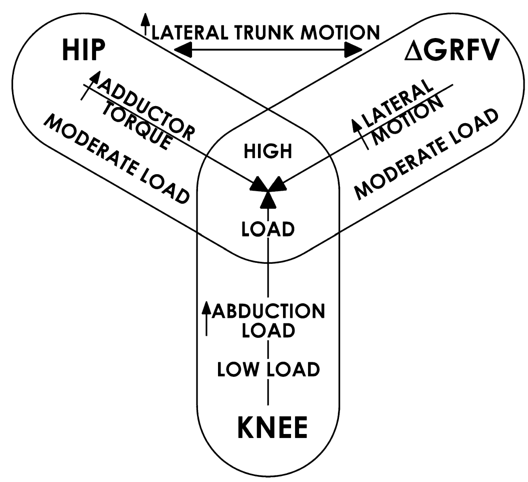

Figure 3. Conceptual model of lateral trunk motion leading to increased ground reaction force vector (ΔGRFv) and hip adductor torque and knee load.

ACL injuries, the ACL, rather than the medial collateral ligament (MCL), can be the primary restraint to knee abduction loads (55). Knee load and ACL injury may be outcomes that result from an unstable, collapsing lower extremity column under axial load (GRF) passing through the lateral knee compartment.

Neuromuscular Trunk Control Mechanisms may Increase Knee Load in Female Athletes

Trunk stability is related to the ability of the hip to control the trunk in response to forces generated from distal body segments, as well as from unexpected perturbations (23,36). Deficits in neuromuscular control of the trunk during cutting and landing may lead to uncontrolled lateral trunk motion that may increase knee abduction motion and torque through mechanical (lateral GRF motion) and neuromuscular (increased hip adductor torque) mechanisms (18,20). Insufficient neuromuscular control of the trunk may increase strain on the ACL and lead to injury via either one or both of these mechanisms (3,18,22,27). Neuromuscular control of the hip is required to control coronal plane trunk and pelvis motion. An external hip abduction moment created by the GRF moving lateral to the center of the femoral head is counterbalanced internally by hip adductor torque (22).

The Underlying Mechanisms — Growth in the Absence of Sufficient Power?

Following the growth spurt that occurs during maturation, female subjects have very different neuromuscular control profiles than male subjects. Recent published studies have observed that male subjects experience a significant increase in neuromuscular strength and coordination as skeletal growth and maturation progresses, a so-called neuromuscular spurt not often observed in female subjects (21,41). As bone length and body mass increases, male subjects also demonstrate greater neuromuscular control of the knee joint than female subjects, allowing them to better absorb loads (Fig. 1). In lay terms, growth results in larger machines in both sexes, but as male subjects mature, they adapt with disproportionately more muscle "horsepower" to match the control demands of their larger machine. Female subjects do not show similar adaptations. In the absence of neuromuscular adaptations in strength and muscle recruitment, female knees are exposed to greater GRFs and high external knee abduction moments (load), particularly in landing, pivoting, and deceleration sports. Collectively, these studies have driven the central hypothesis that increased bone length and body mass, in the absence of matching adaptations in neuromuscular strength and coordinated muscle recruitment, expose the female knee to greater load and likelihood of ACL injury (Fig. 2) (20–22).

Female subjects activate the hip musculature differently than male subjects in response to sudden loading (12). Women adduct the hip more than men during both low- and high-intensity activities. They begin descent in a more abducted knee position and remain in a more abducted alignment relative to men throughout a squat motion or during landing (16). Female subjects also demonstrate more hip adduction than male subjects during cutting (39). Increased hip adduction during dynamic motion and decreased hip muscle abductor strength and recruitment can increase knee load and injury risk (16,20). Ipsilateral trunk lean is a sign of weak hip abductors as it moves the center of mass closer to the stance limb to reduce demand on the weak abductors (51). During single leg landing and cutting, the entire body mass must be balanced over one lower extremity. Because the trunk comprises greater than half of the body's mass, lateral trunk motion increases GRF and load (51). The internal response is an equal and opposite increase in the counterbalancing hip adductor torque (54). The resulting increase in relative hip adductor-abductor torque ratio then likely increases knee load.

Based on the current literature, it is hypothesized that increased lateral trunk motion, change in direction of the GRF velocity (ΔGRFv) and hip adductor torque increase knee load of female athletes (22). Deficits in neuromuscular control of the trunk may contribute to lower extremity joint instability and injury (24). Landing and cutting require high levels of neuromuscular control to maintain stability and performance (35). Dynamic stability of the knee is dependent on accurate sensory input and appropriate motor responses to rapid changes in body position during cutting and landing (20,24). Neuromuscular control of the hip, trunk, and knee is based on feedback control. The position and load of each segment is used to modify the descending movement commands (11). Impaired control of the hip and trunk can increase lower extremity injury. For example, abdominal muscle fatigue contributes to hamstrings injuries (7). Subjects with ankle sprains had a delay in onset of gluteus maximus and medius activation (2). Female, but not male, athletes who experienced ankle injury had greater body sway before injury than uninjured controls (4).

Effects of Neuromuscular Training in Female Athletes

Movement biomechanics and lower extremity strength can be altered in female subjects with neuromuscular training (25). Neuromuscular power (*i.e.*, rate of muscular recruitment and force generation, as evidenced by vertical jump height) can increase within 6 wk of training and may result in decreases in peak impact forces and knee abduction torques (25). Observed changes in female subjects may be greater than those in male subjects as their baseline neuromuscular performance levels are lower (31). If neuromuscular training can decrease ACL injury risk, it is likely that the mechanisms underlying increased risk are neuromuscular in nature (19). ACL injury risk may be reduced in trained female athletes during landing and cutting (15). Elite female athletes show reductions in ACL injuries with neuromuscular training (47). These prospective studies indicate that neuromuscular training has the potential to decrease ACL injury rates in female subjects.

Neuromuscular control of the trunk and lower extremity can be improved with neuromuscular training (20,25,40). Neuromuscular training may increase coronal plane trunk and hip control in female subjects (25,31). For example, during a drop-jump, a two-footed plyometric activity, post training results showed that lower extremity valgus was reduced at the hip. Conversely, during a single-leg landing task, the most significant modifications may occur at the knee (44). Therefore, the effects of training in the coronal plane are likely to be movement task specific. These results indicate that resultant load is controlled primarily by hip torque during a two-foot landing but more by ΔGRFv during single leg tasks. Increased coronal plane control at both the hip and trunk may be necessary to reduce ACL injury risk (6,38). Lower extremity coronal joint motions and torques linked to increased ACL injury risk often are correlated, indicating that control of knee load may require synergistic and antagonistic contribution from the trunk, hip, and knee (20). Perturbation-enhanced training may increase trunk control and decrease knee abduction load in female subjects (29,45).

Female subjects tend to utilize greater coronal plane control rather than a sagittal plane control strategy for the lower extremity (8,10). They tend to utilize a "hip strategy" for single leg control and balance during landing and cutting (9,16). For example, coronal plane excursions are greater and more rapid at the hip and knee during walking in female subjects (29). The knee functions optimally as a sagittal plane hinge, not a coronal plane hinge or ball and socket joint, as the large muscles of the lower extremity that control coronal plane trunk, hip, and knee motion or torque absorb and dissipate force most effectively and efficiently in the sagittal, rather than coronal plane. Women also demonstrate less active joint stiffness than men (28).

Future Directions to Improve Trunk Control Reduce Dangerous Knee Loads and Prevent ACL Injury

So what are the next steps in the decipherment of this hidden, chaotic, and destructive process? First, the newly developed interventions to be tested must target all planes of motion. Future study designs must be rigorous and must employ randomized, controlled trials, with placebo or sham treatments in place. Sham treatments must be in place to control for bias, confounding, unnecessary error, and potentially erroneous misrepresentation of treatment effects. Moreover, result interpretation may be the most common and greatest offender and must be avoided in investigations focused on the effects of intervention on risk factors to female athletes.

SUMMARY AND CONCLUSIONS

This *Perspective for Progress* has provided a strong, evidence-based rationale for the development of effective "core-based" interventions to decrease ACL injury risk in high-risk female athletes. Decreased control of lateral trunk motion and the associated increased hip abductor muscle recruitment and strength likely has a direct effect on the knee abduction loading of the ACL during cutting and landing. Although ACL injuries likely occur too quickly (<100 milliseconds) for reflexive muscular activation (>100 milliseconds), athletes can adopt preparatory muscle recruitment and movement patterns that reduce the probability of injuries caused by unexpected perturbations (32,52). The current evidence indicate that decreased neuromuscular control of the trunk leads to increased joint load (knee abduction moment) via two mechanisms (lateral motion of the GRF and reactive hip adduction torque) and results in increased ACL injury risk in female athletes (Figs. 1–3). One would theorize that knee load (the measurable symptom that increases ACL injury risk) will be decreased by neuromuscular training designed to increase coronal plane trunk stability (22). Further evidence supports the contention that increased load will be decreased by neuromuscular training that enhance coronal plane control of trunk via decreased ΔGRFv and hip adductor strength and recruitment (22,40,41,45). Knowledge of these mechanisms also may be used to categorize female athletes into high-, moderate-, and low-risk groups to allow for targeted training to underlying mechanics of load, which may maximize the effectiveness of neuromuscular training programs aimed to reduce injury risk in female athletes.

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