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INVITED CLINICAL COMMENTARY

UNDERSTANDING AND PREVENTING ACL INJURIES: CURRENT BIOMECHANICAL AND EPIDEMIOLOGIC CONSIDERATIONS - UPDATE 2010

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ABSTRACT

This invited clinical commentary summarizes the current state of knowledge in the area of prevention of anterior cruciate ligament (ACL) injuries. ACL injuries occur with a four to six fold greater incidence in female compared to male athletes playing the same high risk sports. The combination of increased risk of ACL injury and a 10-fold increase in sports participation since the enactment of Title IX in 1972 has led to an almost epidemic rise in ACL injuries in female athletes. Examination of the mechanisms responsible for this sex disparity in ACL rupture accelerated in the last two decades. A summary of these findings and a synthesis and framework for understanding the results of the intense investigation of this research are detailed herein. This clinical commentary focuses on the current understanding, identification and interventional targeting of the primary neuromuscular and biomechanical risk factors associated with the ACL injury mechanism in high-risk individuals.

Key Words: Female, ACL injury, prevention strategies

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INTRODUCTION

Anterior cruciate ligament (ACL) injury occurs with a four to six fold greater incidence in female athletes compared to males playing the same landing and cutting sports.[1] The elevated risk of ACL injury in females coupled with the 10-fold increase in high school and 5-fold increase in collegiate sport participation in the last 30 years has led to a rapid rise in ACL injuries in females.[2-3] This increase in ACL injuries in the female sports population has fueled intense examination of the mechanisms responsible for the gender disparity in these debilitating sports injuries.[4-12] ACL rupture is costly, with conservative estimates of surgery and rehabilitation at $17,000-$25,000 per injury.[6, 13] This is in addition to potential loss of entire seasons of sports participation, decreased scholarship funding, lowered academic performance, long term disability, and significantly greater risk of radiographically diagnosed osteoarthritis.[14-15] The mechanism underlying gender disparity in ACL injury risk is likely multi-factorial in nature. Several theories have been proposed to explain the mechanisms underlying the gender difference in ACL injury rates. These theories include related extrinsic (physical and visual perturbations, bracing, and shoe-surface interaction) and intrinsic (anatomic, hormonal, neuromuscular, and biomechanical differences between genders) variables. This clinical commentary focuses on the authors latest understanding of the identification of the neuromuscular and biomechanical risk factors associated with the ACL injury mechanism and provides direction for targeted prophylactic interventions for high-risk individuals.

ACL INJURY RISK PREDICTION

Using coupled biomechanical-epidemiological approaches, the authors have studied young athletes in Boone County, Kentucky for nearly a decade.[16-18] In that county school system the authors have been tracking all the sixth- through twelfth-grade female soccer, basketball, and volleyball players, by assessing biomechanical performance and following the athletes longitudinally for injury. Load and biomechanical profiles of young athletes can be studied in order to determine how these profiles relate to biomechanical and neuromuscular factors, as well as to determine how they underlie future risk for ACL injury as the athlete's age. These same profiles are also being studied regarding their relationship to patellofemoral pain syndrome, juvenile osteochondritis dissecans, and osteochondral defects. The coupled biomechanical-epidemiological approach has allowed the authors to develop a much greater understanding of the critical ages when females appear to be most vulnerable to injury, as well as the strategies that can be undertaken in order to prevent and treat ACL injuries.[16, 19-21]

When video sequences of actual ACL injury are examined, it appears that there are four common motor performance components that occur, especially in women.[16, 22] As the at risk female athlete lands, her knee buckles inward. The injured knee is relatively straight. Most if not all of her weight is on a single lower extremity. Finally, her trunk tends to be tilted laterally. In summary, her center of mass is outside of her base of foot support. These same mechanisms also occur in men but the exaggeration of the positioning of the lower extremities and trunk is much greater in women.

Directly related to the aforementioned four common components of the typical mechanism of injury are four neuromuscular imbalances that the authors term ***ligament dominance***, ***quadriceps dominance, leg dominance, and trunk dominance***. Existing evidence suggests that these four neuromuscular imbalances may be associated with the underlying ACL injury mechanisms. Therefore, these imbalances should be screened for and indentified in individual athletes. Identification of faulty movement patterns would allow for implementation of specific interventions, targeted at prevention.

Ligament Dominance

Recall the component of the typical injury mechanism where the knee collapses into a valgus position. The neuromuscular imbalance observed more frequently in women than men responsible for this biomechanical deficit is termed ***ligament dominance***. In the condition termed ligament dominance, muscles do not sufficiently absorb the ground reaction forces, so the joint and the ligaments must absorb high amounts of force over a brief time period. High amounts of force sustained over a short period of time lead to higher impulse forces, which is what likely results in ligament rupture.

Ligament dominance is characterized by use of anatomic (bony configuration and articular cartilage) and static stabilizers (ligaments) to absorb the ground reaction forces encountered during activity, rather than the use of the muscular prime movers of the lower extremity. Especially important for lower extremity muscular control (and avoidance of ligament dominance) is the group of muscles that comprise the posterior kinetic chain: the gluteals (both maximus and medius), the hamstrings, and the gastrocnemius and soleus. The large, powerful posterior chain muscles must be properly recruited in order to absorb the substantial reaction forces imparted by the ground, or they travel to the joint and the ligament. Newton's third law of equal and opposite reaction forces is always obeyed. Therefore, when a female soccer player makes a one-footed cut on the field, or a female basketball player lands from a rebound on a court, she hits the ground or court, and that surface hits her back with an equal and opposite reaction force. The reaction force experienced by the athlete is actually significantly greater than her body weight because her body and body segments have inertia and impart a force to the ground greater than their collective mass. These inertial properties related to velocity of movement lead to forces in multiples of body mass impacting the ground and body. For example, when a female athlete is simply walking across the court, she is impacting the ground and the ground is impacting her back with two to three times her body mass. Forces experienced during the landing, cutting, running and jumping tasks performed during sports activities occur in multiples of body mass much greater than two to three times.

During all activities, the ground reaction force (GRF) is directed toward the center of mass (COM) of the body. The COM, which resides in the trunk segment of the body, is the target of the GRF, and therefore the trunk and control of trunk motion is vitally important for control of GRF's imparted to the body. In addition to the trunk, the positioning of the COM relative to the knee joint and the plantar surface of the foot is crucial with regard to knee protection or injury. The trunk plays a crucial role in the female athlete's ability to control her body in space. This will be further discussed in the upcoming section on trunk dominance. However, in the context of ligament dominance, if the trunk moves, the GRF tracks or follows the movement of the trunk; if an athlete allows her trunk to move laterally, her center of

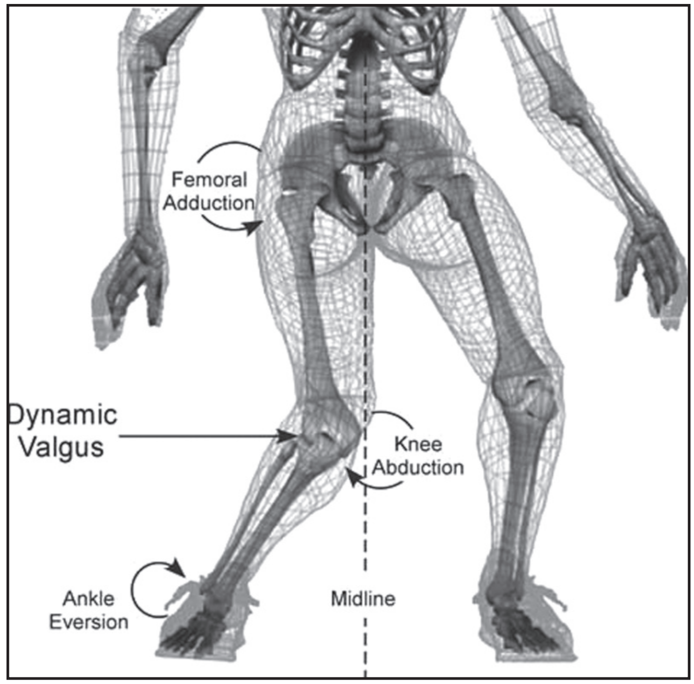

Figure 1. *Example of dynamic lower extremity valgus: A combination of motions and rotations at all 3 lower extremity joints, potentially including hip adduction and internal rotation, knee (tibial) abduction, tibial external rotation and anterior translation and ankle eversion.*
Figure reproduced from Hewett, TE, 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. Used with permission, Sage Publications.*

mass moves with it. As the GRF tracks the COM, and if it progresses lateral to the center of the knee joint, the result is movement of the knee joint into a valgus alignment. Thus, the problem with excessive lateral trunk motion or the lack of adequate neuromuscular control of the motion of the trunk in the frontal plane during sports movements: the ground reaction force moves in the direction of the center of mass, lateral to the knee joint, and forces the lower leg into an abducted position (valgus position at the knee). (Figure 1)

Quadriceps Dominance
Recall that females tend to land from a jump with less knee flexion than males. The extended knee joint component of the injury mechanism relates to a neuromuscular imbalance that occurs in females that the authors term ***quadriceps dominance***. Quadriceps dominance refers to the tendency to stabilize the knee joint by primarily using the quadriceps muscles. Women appear to preferentially use the quadriceps

more than males in order to stiffen and stabilize the knee joint.[5] When females contract their quadriceps it extends their knee, which likely relates to the more extended knee position observed during an ACL injury. In addition to that, the quadriceps serve to stiffen or compress the tibiofemoral joint. The common quadriceps tendon attaches at the superior patella, and then attaches via the infrapatellar tendon to the tibial tubercle on the anterior tibia. When the quadriceps contract they pull the tibia anterior relative to the femur. The resultant biomechanical problem is that the ACL serves to hold the tibia posteriorly (or check anterior translation), and when a female athlete uses her quadriceps to stabilize the joint she induces an anterior shear stress to the tibia and therefore also to the ACL.

Quadriceps dominance relates to ligament dominance. If an athlete preferentially uses the quadriceps instead of the posterior chain muscles to control the limb, she uses a single muscle with a single tendinous insertion for stability and control. This is in contrast to using the group of posterior chain muscles that possess multiple muscles with varied tendon insertions that can be selectively utilized to control the limb during functional tasks. For instance, the hamstring has both medial and lateral tendons that play a vital role in stiffening and stabilizing the knee joint, in the exact opposite direction of the quadriceps at low knee flexion angles. The hamstrings are able to increase flexion at the knee, which provides a better position (mechanical advantage) for using the muscles to absorb force. The hamstrings are considered a synergist with the ACL and are able to pull the tibia posteriorly thereby decreasing the stress on the ACL. Finally, the hamstrings have tendons that insert on either side of the joint that can offer the frontal plane control of motion at the knee that is vital for injury prevention.

The authors' early studies compared high school male and female volleyball players who were on average the same weight and height. Hence, biomechanically, they were quite similar.[5] When an athlete blocks a volleyball over a net, two significant force spikes occur right at the point of landing, when the ball of the foot hits and when the heel hits. These forces are in the range of five to seven times body weight. The athlete's center of mass is forward because he/she just blocked the ball over the net, and the landing knee is often near full extension, demonstrating the lack of knee flexion.

If the athlete's COM is forward and the knee is extended, the GRF (when assessing from the side, in the sagittal plane) slams the knee back further into extension. In biomechanical terminology this is referred to as an external force, because the force is coming from the ground. In essence, as the athlete hits the ground, the ground offers an external extension force which extends the hinge of the knee joint. As previously mentioned, according to Newtonian mechanics the mechanisms inside the body must generate an equal and opposite torque in order to prevent the athlete from falling backwards. That torque is called an internal flexion moment or flexion torque, and it is provided mainly by the hamstrings and gastrocnemius at that point of landing. Deficits in recruitment of hamstrings and gastrocnemius during landing may allow for excessive extension torques that increase stress on knee joint passive stabilizers, and provide enough torque to cause injury. The authors of this commentary further determined in the same study of volleyball players that the posterior kinetic chain muscles that flex the knee were activated at three times the level in size-matched males as compared to females when landing from a jump.[5] This early study provided documentation of ***quadriceps dominance*** in women[5]. Other researchers examined the muscular reactions that occurred after pushing the tibia forward with an experimental turnbuckle device. In this study, men activated their hamstrings first, while females first activated their quadriceps.[23] In summary, primary activation of the hamstrings is desirable because the hamstrings pull the tibia posteriorly and take stress off the ACL. The quadriceps first muscular control strategy used by women, where the quadriceps pull forward adding to the anterior stress on the ACL, is exactly opposite of the preferred activation pattern used by males.

Leg Dominance

The authors call the third type of imbalance ***leg dominance***. In tasks that normally require side-to-side symmetry of the lower extremities, women tend to be more one-leg dominant than their male counterparts. When a female tears her ACL, most if not all her weight is on a single leg.[22] When considering the imbalance of leg dominance, it should be acknowledged that most athletes have a preferred plant leg and a preferred kick or drive (in the case of a single leg jump task) leg. However, the difference between limbs in muscle recruitment patterns, muscle strength, and muscle flexibility, tends to be greater, in women than men.[10, 21, 24-26] So, in the context of a preseason screening process neuromuscular/biomechanical tests should attempt to identify side-to-side differences. Regarding muscular symmetry, if side to side muscle strength or relative recruitment differences are measurable, then an athlete is asymmetric and is considered to be leg dominant. What the authors of this commentary have shown is that those that have greater asymmetry in these force and torque profiles have greater risk of future injury.[20]

Trunk (Core Dysfunction) Dominance

Those athletes, typically women, who do not adequately sense the position of their trunk in three-dimensional space, or allow greater movement following a perturbation or disturbance of their trunk, have greater risk of future knee, ligament, and ACL injury.[22, 27] Diminished proprioception of the trunk is one difference that exists between men and women. In women a valgus positioning of the knee is frequently observed during varied motor tasks, and is considered to be high risk for ACL injury. The same positioning is not frequently observed in men, and the trunk is a more common contributor to the at risk position demonstrated by women. For instance, in those studies performed by Zazulak et al[27-28] on the association between trunk proprioception and control and future risk of knee ligament injury, trunk motion and trunk proprioception predicted risk of future knee ligament injury in females, but not males.[27]

Trunk dominance is simply defined as the inability to precisely control the trunk in three dimensional space. Trunk dominance may be related to growth and maturation factors. For example, if you observe a young woman who has just experienced a growth spurt; she has a bigger "machine" to manage with her existing motor programs and neuromuscular strategies. This growth spurt may be likened to putting someone on stilts. So, if an average 10 or 11 year old female grows ten to fifteen centimeters (4-6 inches) in a year she basically functions as if on stilts. As females mature, they also increase body mass and add proportionally more fat body mass than their male counterparts. Her center of mass is higher off the ground, therefore, it is harder for her to control and balance her body. After the adolescent growth spurt, males get what is called a "neuromuscular spurt" where they experience muscular development and get proportionately more powerful. So, although males also get a bigger "machine" after a growth spurt they get a much bigger sized engine in relation to the size of the machine. In contrast, in women and girls, that ratio between the size of the machine and the size and the power output of the engine, basically stays the same and does not adapt to the increased demands.

After maturation, females experience a more massive trunk, a center mass located higher off the ground and fat and lean body mass redistributed in novel ways, but don't get the more powerful engine to control that bigger "machine". When examining videos of a woman rebounding a basketball or cutting on the soccer field, she will frequently have excess motion of the trunk. Recall, that as discussed in the context of ligament dominance, the uncontrolled side to side movements and GRF's create medial-lateral torques on the knee.

In summary, the authors believe that these four neuromuscular imbalances underlie the mechanisms that relate to ACL injury risk that is greater in females than in males. We have demonstrated these four dysfunctional movement strategies both in the controlled environment of the laboratory and during sport performance and injury analysis on the field or court. Acknowledging that there are differences between males and females in the observed ACL injury mechanism, it is important to understand the important variations observed in prevention strategies.[29] When interventions are designed, the observed differences in injury mechanisms should be considered and unique programs that specifically address the neuromuscular deficits observed should be developed for males and females. For example, in females there should be a greater focus on dynamic, ground based core or dynamic trunk training than in a program developed for males.[27-28]Authors have demonstrated that single limb balance and wobble board training is more important for men than women, who are on average more proficient than men at single leg balance. Hence, single limb balance training

Table 1. *Relationship between Mechanism, Neuromuscular Imbalance, and Neuromuscular Intervention for ACL Injury Prevention in Female Athletes.*

Injury Mechanism Component	Underlying Neuromuscular Imbalance	Targeted Neuromuscular Intervention Component
Knee adduction during landing	Ligament dominance	Train for proper technique
Low flexion angle in landing	Quadriceps dominance	Strengthen posterior chain
Asymmetrical landings	Leg dominance	Train side/side symmetry
Inability to control center of mass	Trunk dominance ("Core Dysfunction")	Core stability & perturb training

should be included when designing an ACL prevention program specifically for men.[30-31]

Interventions to address Quadriceps Dominance

After conducting two decades of research investigations and closely following the emerging evidence published by other researchers, it has become apparent that females are in fact highly quadriceps dominant. The authors believe that the muscles of the posterior chain are present, but are often under-recruited or not effectively "turned on" in many female athletes. For instance, Zazulak et al presented data regarding hip muscular recruitment of women and men, showing that women activate their hamstrings and gluteals less than men.[32] The gluteus maximus, the biggest, strongest muscle in the body, is the only triaxial, three plane controller of femoral position. When an athlete primarily contracts her quads, and reduces the contraction of her gluteals and hamstrings, the result is the position of valgus knee collapse. Recall that this is problematic because as an athlete allows the ground to push her knee into the valgus position, her muscle contraction patterns further reinforce that position and the loads experienced at the knee can become high enough to be injurious.

Interventions to encourage female athletes to become less quadriceps dominant emphasize "turning on" or emphasizing the recruitment of the posterior kinetic chain muscles. This can be achieved in multiple ways. Plyometric exercises that utilize the position of 90/90 degrees flexion at the knee and hip are highly effective. (Figure 2) Russian hamstring curls using a band across the chest facilitate control utilizing not

Figure 2. *Squat jump sequence. Note, in a tuck jump the knees are flexed toward the trunk while in the air. See Appendix 1 for more detail on the tuck jump.*

Figure reproduced from: Myer GD, et al. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. J Athl Train. *2004;39(4):352-364. Used with permission, Journal of Athletic Training.*

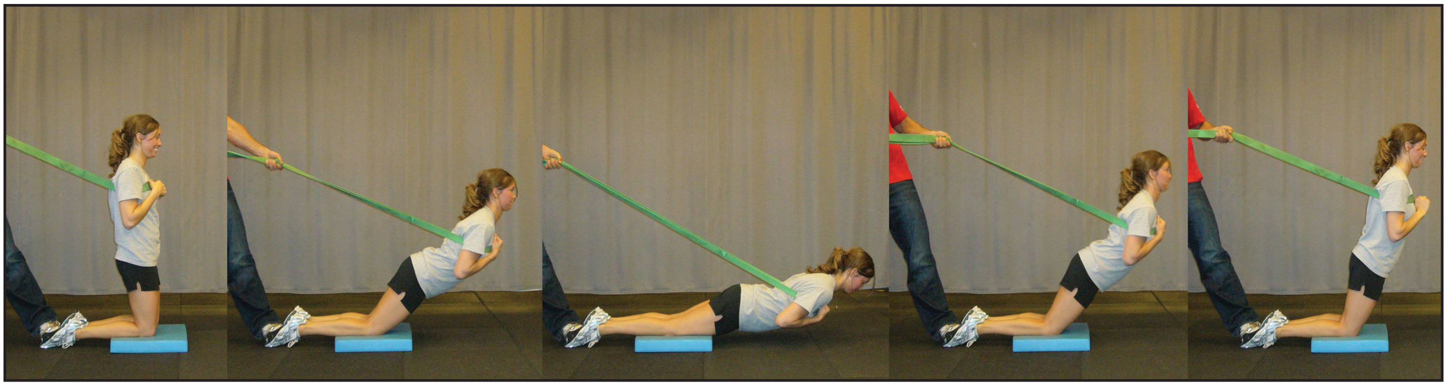

Figure 3. *"Russian" hamstring exercise with elastic resistance around the trunk to emphasize concentric and eccentric hamstring contractions.*

only the eccentric (lowering) part of a closed kinetic chain hamstring curl, but also the concentric (raising) part. (Figure 3) Athletes benefit by training all muscles of the posterior kinetic chain in both eccentric and concentric modes.

The authors also use exercises that enhance recruitment of the posterior chain while requiring core activation of the abdominals and hip stabilizers. Instruct the athlete to put their heels on a medium size swiss ball, and assume a plank position, maintaing a neutral pelvis (a flat body position) and then pull the knees into flexion, by rolling their heels on the ball. The athlete pulls the ball toward their rear-end by flexing the knees, achieving a dynamic hamstring curl while the pelvis remains stable. (Figure 4) To increase the difficulty, the athlete can do the same movement using a single leg which incorporates both balance and strengthening work.

Interventions to address Leg Dominance

Single leg balance and single leg hopping techniques are useful for addressing leg dominance. (Figure 5) Although it may seem counterintuitive, the more single leg activities an athlete performs, the more side to side symmetry is restored. The human body possesses complex neurologic mechanisms that attempt to achieve balance, one side versus the other. This is especially true when performing single leg tasks; the body makes use of neuromuscular feedback loops and bilateral neurological systems to influence symmetry during dynamic control of such tasks. Note

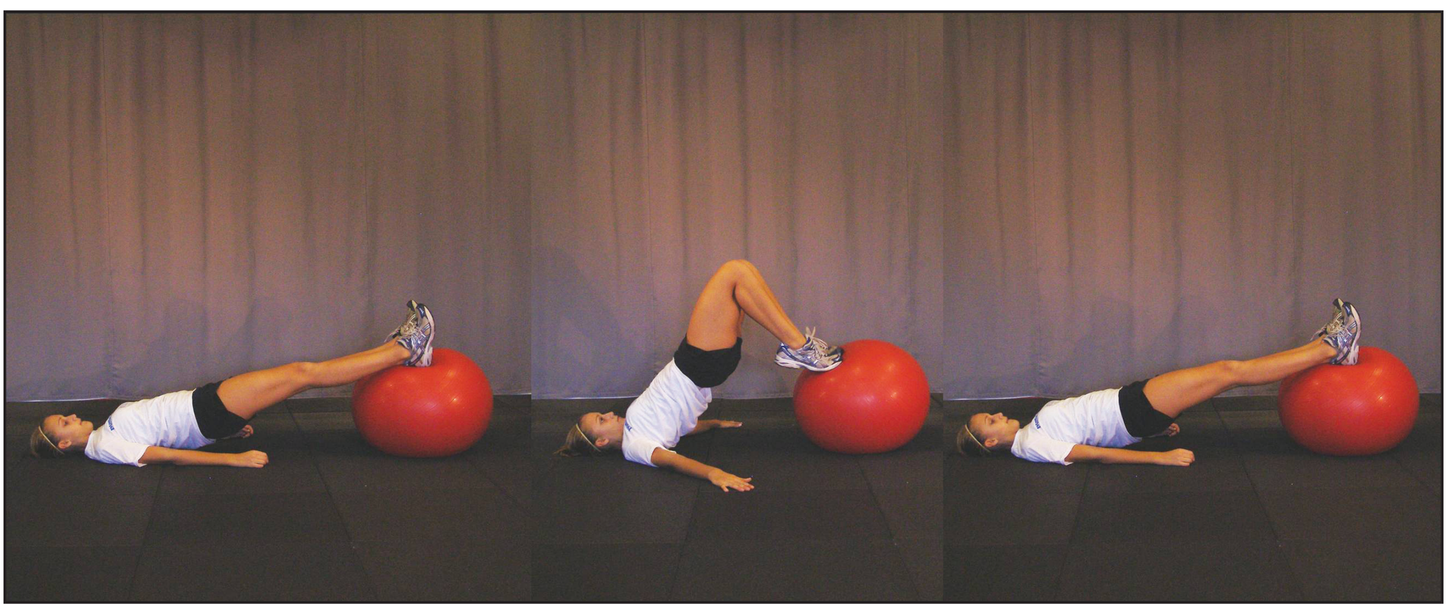

Figure 4. *Dynamic core stabilization and hamstring curl on swiss ball. Note: the athlete must stabilize the trunk/core as the legs flex and extend.*

Figure reproduced from: Myer, G. D., D. A. Chu, et al. Trunk and hip control neuromuscular training for the prevention of knee joint injury. Clin Sports Med. *2008;27(3): 425-448, ix. Used with permission, Clinical Sports Medicine.*

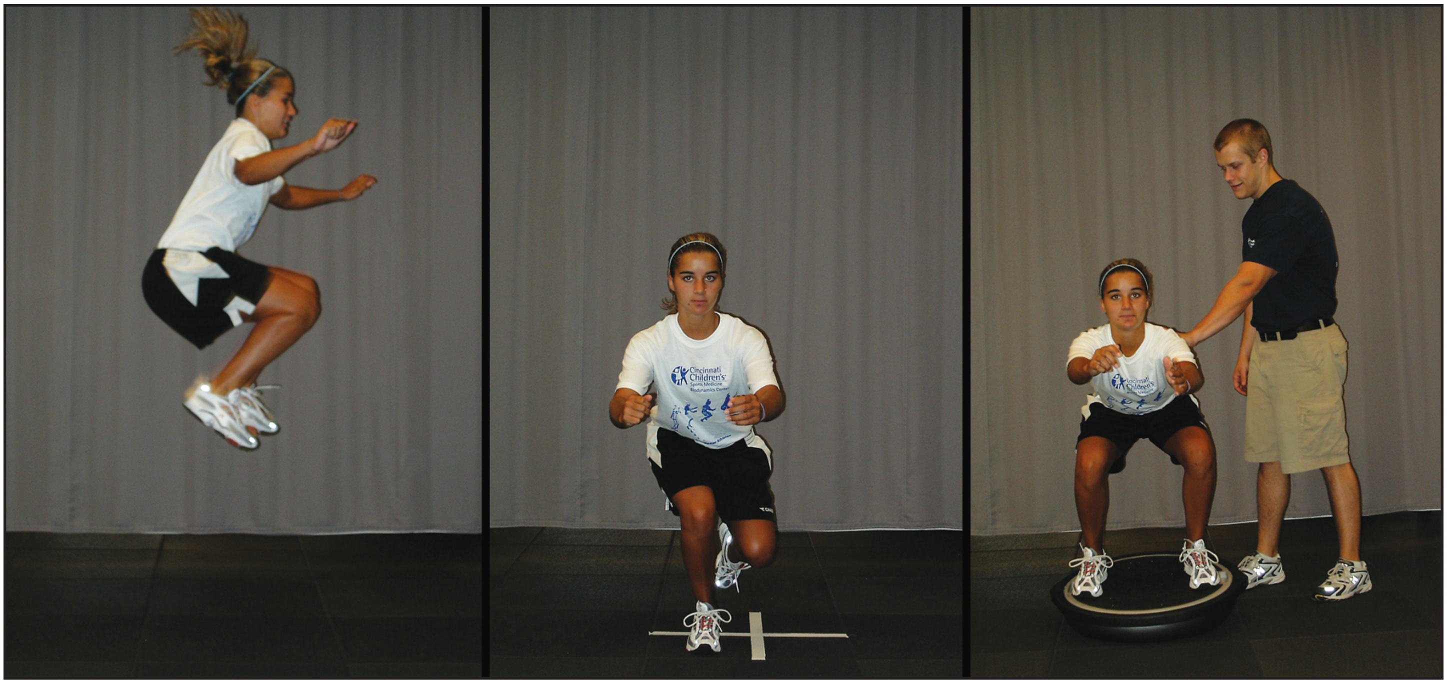

Figure 5. *Example of three components of dynamic neuromuscular training: plyometrics, single limb balance, and perturbations. Note: Single limb balance and perturbations are especially helpful in decreasing leg dominance.*
Figure reproduced from: Hewett TE, et al. Anterior cruciate ligament injuries in female athletes:Part 1, mechanisms and risk factors. Am J Sports Med. *2006;34(2):299-311. Used with permission, Sage Publications.*

that maximum cross-over effects are achieved when both lower extremities are utilized in single limb activities, alternately. Additionally, single leg hop activities may influence synergistic recruitment of the posterior chain musculature, which facilitates not only the muscular control to be successful with unilateral tasks, but may also decrease quadriceps dominance during dynamic tasks.

Interventions to address Trunk Dominance

Addressing trunk dominance is achieved by core training, but not necessarily the core training related to the increase in performance of the prime movers (such as the rectus abdominis). Instead, contemporary focus regarding training for the core relates to the specific instruction in activities that provide stability offered by the local musculature (such as transversus abdominis and multifidus) and pelvic/hip stabilizers. Trunk dominance is difficult to measure in real time, especially during dynamic function. Many of the training techniques described within this commentary are testing procedures at the same time. The swiss ball exercise described previously (see Figure 4) can be used as a measure of an athlete's ability to control their core, by assessing the stability of the pelvis in the transverse and frontal planes. When an athlete lacks core stability the pelvis deviates into rotated or anterior/posterior tilted positions.

Another important consideration of core stability is the ability of the patient to control the pelvis on the hips and lower extremity in space via the stabilization functions of the abductors and rotators of the hip. Therapists who work with athletes after an ACL tear and subsequent reconstruction should be aware that one of the best predictors of future risk is hip external rotation strength. The hip external rotators serve as a proximal stabilizing component of the core and lower extremity. In a recent article published by Paterno et al, subjects whose hip external rotation strength was less than optimal after an ACL reconstruction had an eight times greater chance of sustaining another ACL injury.[21] An exercise to address the hip rotation facet of core control is closed chain internal and external rotation of the hip using elastic resistance. (Figure 6) In this exercise the patient assumes a single limb stance position, wraps elastic tubing around their pelvis and concentrically and eccentrically controls the transverse plane rotation/derotation of the pelvis on the hip, while keeping the trunk erect. Feedback about

Figure 6. *Closed-kinetic chain hip internal and external rotation using elastic resistance. Elastic resistance is secured lateral to the pelvis at the level of the hip/pelvis, and is wrapped around the pelvis in order to exert a pull opposite the desired rotation. The athlete assumes single limb stance on the leg to be trained. The contralateral limb is flexed at the hip and knee. The athlete contracts the external rotators of the hip, thereby moving the pelvis on the femur, in this case into a relatively externally rotated position. (Figure 6A) Eccentric control by the hip external rotators is required to return to neutral position and beyond into an internally rotated position. (Figure 6B) Close attention must be paid to the position of the pelvis, to not allow alterations in the frontal (Trendelenburg) or sagittal plane (anterior or posterior tilt).*

maintaining upright posture and neutral pelvic position both the sagittal and frontal planes is essential.

Finally, those athletes that went on to sustain a second ACL injury had increased frontal plane excursion of the trunk and knee, and decreased flexion through the knee and hip during sport competition.[21] Trunk deviations seem to be closely related to lower quarter deviations as previously described in the discussion about the COM and base of support relationship to valgus positioning of the lower extremity. If athletes allow significant medial collapse at the knees they had approximately a four and a half fold greater risk of injury. If athletes showed asymmetry during landing, one side versus the other, they had about three times greater risk of a second ACL injury.[21]

THE APPROACH FOR PREVENTION: ADDRESSING THE PROBLEM

Picture the female athlete landing during sport performance; the knee is relatively straight and collapsing into valgus. Most, if not all of the weight is on a single foot, and the trunk is tilted to one side. These four neuromuscular imbalances comprise the formula for an ACL tear. The contributory factors for each are well described, and are affected either directly or indirectly by the position of the trunk. Each of these neuromuscular imbalances contributing to the mechanism of injury can be affected by targeted training. The athlete must be taught the following concepts for correct neuromuscular control during motor tasks: the trunk should not swing side to side during motion; the knee should not collapse medially; the posterior chain musculature must be turned on so that her knee is in a position of controlled flexion and she uses the correct muscles to absorb forces; and she must use her lower extremities equally.

Many studies and several meta-analyses of the literature have shown that the prevention programs that incorporate the above stated concepts and directly address the four critical neuromuscular imbalances that directly relate to injury mechanism, reduce injury risk between 30 and 80 percent.[18, 26] If a girl or woman is five times more likely than a boy or man to rupture her ACL, an intervention that can gradually decrease risk from five times down to one reduces the risk by 80 percent, creating an equal injury rate between males and females. Some of the current popular intervention or prevention programs have been shown to be able to drop the risk experienced by females down to male levels.[33] On average, interventions can drop risk by about 50 percent (risk is cut approximately in half) which is a huge effect on relative risk provided by neuromuscular training.[6]

The authors have shown that the effects of specific interventions on the four neuromuscular imbalances are great. As an example, when first examining the effects of knee abduction torque (which forces the knee into the valgus position) on the knee, subjects showed a 50 percent reduction in torque at the knee after participation in a neuromuscular and strengthening program.[5] Subsequently, in a follow up clinical study, the authors showed a 50 and 60 percent drop in relative risk after participation in a neuromuscular training program.[6] Thus, knee torques that push the knees inwards, are directly related to relative risk.

Second ACL injury is a major problem. The risk in the general population, and especially in the young female population, of first time tear of the ACL is somewhere between 1 in 50 and 1 in 100.[26] After young female athletes tear their ACL and undergo reconstruction, their risk of rupturing their ACL ***again*** is near 1 in 4.[21] Hence, therapists should be aware of, screen for, and attempt to correct all identifiable neuromuscular deficits prior to returning an athlete to sport participation subsequent to an ACL reconstruction and the associated rehabilitation. The neuromuscular control deficits demonstrated by many female athletes may have been present prior to the initial ACL rupture. Such deficits may worsen after the ACL is ruptured, because the mechanoreceptors that comprise a significant percentage of the ACL are damaged and no longer functional. Hence, physical therapists must address neuromuscular deficits specifically and have a strong focus on preventative type training in order to help the athletes compensate for the loss proprioceptive sensors of 3-D kinematics and kinetics in the knee. Prevention of subsequent re-injury to the ACL demands careful attention to building the optimal neuromuscular strategies for control of the body during all functional tasks.

DEVELOPMENT AND APPLICATION OF ACL INJURY RISK SCREENING TEST - FROM THE LABORATORY TO THE FIELD

Development of Screening Test

A scientifically based approach is recommended for the development of any strategy designed to prevent sports injuries.[34] The authors have incorporated the sequence of a prevention model[34] to systematically organize specific scientifically based principles that can be used to effectively develop injury prevention programs. The initial steps involve understanding and establishing the extent of the problem based on injury incidence and severity. As detailed earlier, ACL injuries are a significant and extensive problem in female athletes.

The next step in the sequence of injury prevention is to establish the injury mechanism and etiology. The relative importance of each risk factor is difficult to evaluate for each individual athlete. However, a detailed description of the inciting event (injury mechanism) is suggested in order to identify the appropriate methods for injury prevention and to allow for the description of the theoretical potential intrinsic and extrinsic risk factors.[34] The literature is full of information about injury mechanism in females: most ACL injuries occur in a non-contact episode during sport performance, typically during deceleration, lateral pivoting, or landing tasks that are associated with high external knee joint loads.[35-36] Video analysis techniques have confirmed that most non-contact ACL injuries occur during a sharp deceleration or landing maneuver with the knee close to extension at initial ground contact.[36] Olsen et al. performed a videographic examination of ACL injury mechanisms in team handball.[35] They found that the ACL injury mechanism in women was a forceful valgus collapse with the knee close to full extension combined with tibial rotation, validating the contribution of both ligament and quadriceps dominance dysfunctions.

Risk factors for most sports injuries are classified into internal (intrinsic) and external (extrinsic) to the athlete. Risk factors such as age, maturation, and neuromuscular performance may predispose the athlete to injury. The potentially modifiable intrinsic variables of interest in the authors screening program are those that are neuromuscular/biomechanical. Specifically, the authors believe in targeting *altered movement patterns* that may increase ACL injury risk. Altered movement patterns can be described by the specific plane which the majority of the deficit occurs. For example, the sex-based disparity observed in ACL injury rates may be strongly influenced by differences in the frontal plane joint motions and moments. The link between frontal plane knee loading and resultant increases in ACL strain is demonstrated by cadaveric, *in vivo* and computer modeling experiments.[37-40] Physiologic dynamic valgus torques on the knee can increase anterior tibial translation and load on the ACL several-fold[39], also validating the concepts of ligament and quadriceps dominance.

Application of Laboratory Based Screening Test

A prospective combined biomechanical-epidemiologic study showed that knee abduction moments (valgus torques) and angles were significant predictors of future ACL injury risk. Knee abduction moments predicted ACL injury risk with 73% sensitivity and 78% specificity.[20] Knee abduction angles (valgus angulation at the knee) were 8 degrees greater in the ACL-injured group than those in the uninjured groups. It is therefore likely that increases in knee abduction moment and motion in the injured group were significant risk factors that predisposed each athlete to an ACL injury.

Sex differences in knee abduction motion and moment have been investigated in numerous studies during landing maneuvers with three-dimensional motion analysis techniques.[9-10, 41-64] The majority of the studies found an increased knee abduction (valgus) motion or moment in females compared to males. In a recent longitudinal study, Ford et al.[19] identified that during a landing task pubertal females have an increased change in knee abduction motion within a year of rapid adolescent growth. In addition, important reported risk factors of knee abduction motion and torque were significantly greater over consecutive years in young post-pubertal female athletes as compared to males.[19] If pre-season testing methods could identify an athlete who is at higher risk for an ACL injury, coaches may more likely institute and remain committed to injury prevention programs for those athletes.

Application of Clinic Based Screening Test

The presence of altered movement patterns may be responsible for the increased rates of knee injury in females, but is not typically measured in athletes prior to participation. Standard pre-participation physicals assess static measures of joint stability. Few, if any, dynamic measures are assessed during these exams and plans for movement training interventions are rarely implemented. No method for the accurate and practical screening and identification of athletes at increased risk of ACL injury is currently available. The assessment of potential injury risks prior to sports participation followed by targeted intervention aimed at correcting measured neuromuscular imbalances may decrease the relative injury incidence in athletes.[65] Preparticipation screening of athletes may be used to identify those athletes prone to knee injury and who would benefit from a training intervention to enhance strength, proprioception, and neuromuscular stabilization about the knee joint. Simple methods to determine which athletes are at increased risk of injury, which are readily available to coaches, athletic trainers, physical therapists, and athletes, might allow for large scale screening for injury-prone athletes and clearly identify those athletes who need preparticipation training. With the ever-increasing popularity of sports like soccer, volleyball, basketball, and softball, and the rapidly growing number of participants, higher numbers of injuries could be avoided in the future.

Laboratory based screening tools demonstrate that altered neuromuscular strategies or decreased neuromuscular control during the execution of sports movements, as evidenced by abnormal lower limb joint mechanics (motions and loads), may underlie the increased risk of ACL injury in female athletes.[4, 9-10, 20, 66-67] Prospective measures of external knee abduction moment during landing predict non-contact ACL injury risk in young female athletes.[20]

Calculation of knee injury risk factors such as knee abduction moment through inverse dynamics requires complex laboratory-based three-dimensional kinematic and kinetic measurement techniques. Myer et al have described isolated biomechanical measures that contribute to nearly 80% of the measured variance in knee abduction moment during landing.[16] These biomechanical predictors of knee abduction moment, which include increased knee abduction angle, increased relative quadriceps recruitment and decreased knee flexion range of motion (ROM), concomitant with the increased tibial length and body mass (normalized to body height) that accompanies growth, are measurements that have all been related to increased risk of ACL injury in previous prospective and retrospective epidemiological reports.[20, 36, 68-69] Unfortunately, expensive biomechanical laboratories, with the costly and labor intensive measurement tools used to test individual athletes, are required to acquire these measurements. This restricts the potential to perform athlete risk assessments on a large scale, limiting the potential to target large numbers of high injury risk athletes with the appropriate intervention strategies.

In order to achieve the objective of reducing non-contact injury risk in female athletes, identification of those who preferentially demonstrate high knee abduction moment landing mechanics appears salient. Therefore, a field-based assessment algorithm was systematically developed to improve the potential to identify and target injury prevention training to female athletes with increased knee abduction moment.[24-25, 70] The validated field-based assessment algorithm delineated five biomechanical factors that could be captured in clinic and filed settings which, when combined, identify high knee abduction moment during landing with high accuracy.[24-25, 70] (Figure 7) This clinic-based assessment tool can be administered in a clinic or field testing environment. It has been validated by the highly accurate laboratory-based assessment and facilitates screening for ACL injury risk on a more widespread basis. However, it does not as readily allow for real-time feedback from clinicians to utilize during neuromuscular training to correct deficits.

APPLICATION OF A FIELD-BASED FUNCTIONAL ASSESSMENT TOOL

While the above mentioned clinic-based assessment tool is valuable to identify athletes who should be

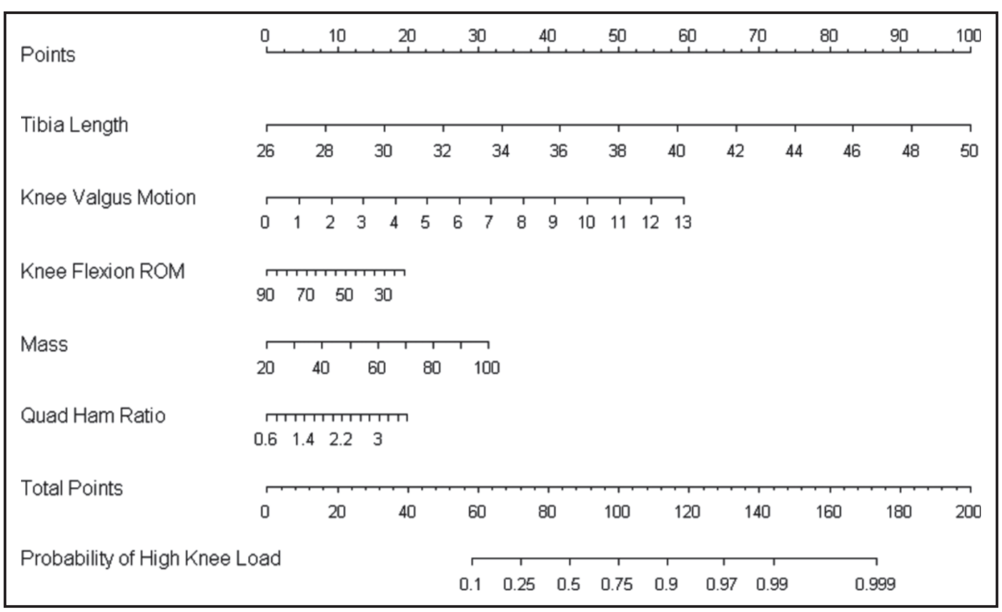

Figure 7. *Injury Prediction Nomogram.*
Figure reproduced from: Myer GD, et al. Clinical correlates to laboratory measures for use in non-contact anterior cruciate ligament injury risk prediction algorithm. Clin Biomech (Bristol, Avon). *2010;25(7):693-699. Used with permission, Clinical Biomechanics.*

targeted with neuromuscular training, it was imperative to develop an additional "clinician friendly" field-based, functional performance landing and technique assessment to identify and then target high risk ACL injury mechanisms. For this reason the tuck jump assessment tool was developed to aid clinician decision making during training sessions.[71] The tuck jump is also well suited as a training tool to improve neuromuscular technique because it incorporates limb symmetry, trunk control, recruitment of the posterior chain musculature, and sagittal plane control of the limbs.

REAL TIME FIELD ASSESSMENT AND TRAINING TOOL

The tuck jump exercise may be useful to the clinician for the identification of lower extremity technical flaws during a plyometric activity.[72] The tuck jump (Figures 1 and 3) requires a high-level effort from the athlete. Initially, the athlete may place most of his or her cognitive efforts solely on the performance of this difficult jumping task. The clinician may readily identify potential deficits especially during the first few repetitions. In addition, the tuck jump exercise may be used to assess and track improvement in lower extremity biomechanics as the athlete progresses through their training.[71-72]

Appendix 1 provides the "clinician friendly" landing technique assessment tool clinicians may use to monitor an athlete's performance of the tuck jump before, during, and after training. Specifically, the athlete performs repeated tuck jumps for 10 seconds, which allows the clinician to visually grade the outlined criteria. To further improve accuracy of the assessment, a standard 2D camera in the frontal and sagittal planes may be utilized to assist the clinician. The athlete's techniques are subjectively rated as either having an apparent deficit (checked) or not. The deficits are then tallied for the final assessment score. Indicators of flawed techniques should be noted for each athlete and should be the focus of feedback during subsequent training sessions. The athlete's baseline performance can be compared to repeated assessments performed at the midpoint and conclusion of training protocols, to objectively track improvement with jumping and landing technique.

TARGETING NEUROMUSCULAR DEFICITS RELATED TO ACL INJURY WITH THE TUCK JUMP ASSESSMENT

For organizational ease, the criteria assessed during the tuck jump tool can be grouped into the neuromuscular risk factor categories described in this clinical commentary. (Figure 8) The tuck jump assessment tool can be utilized to improve techniques (thus decreasing risk) during an exercise that requires a high effort level from the athlete. As suggested earlier, an athlete may place most of his or her cognitive efforts solely on the performance of this difficult

Figure 8. *Tuck jump Criteria grouped into Dominance categories. Figure reproduced from "Myer, G. D., J. L. Brent, et al. (2010). "Real-time assessment and feedback techniques for use in neuromuscular training aimed to prevent ACL injury." Strength and Conditioning Journal* ***In Press****." With permission from the editor.*

jump and demonstrate many technical flaws that are indicative of increased risk for injury. However, if she can improve her neuromuscular control and biomechanics during this difficult jump and landing sequence, she may gain dynamic neuromuscular control of the lower extremity and create a learned skill that can be transferred to competitive play. Empirical evidence from the authors' laboratory suggests that athletes who do not improve their scores, or who demonstrate 6 or more flawed techniques, should be targeted for further technique training. Pilot work in the laboratory indicated that the intrarater reliability for the tuck jump assessment was high r = 0.84 (range 0.72-0.97). These data indicate that this assessment may be adequate for a single clinician to re-assess athletes to determine changes in technical performance of the tuck jump exercise.[73]

CONCLUSIONS: NEUROMUSCULAR CONTROL DEFICITS CAN PREDICT ACL INJURY IN FEMALE ATHLETES

Increased ACL injury incidence in female athletes is likely a multi-factorial neuromusculoskeletal phenomenon. Potential factors that have not been discussed may play a role (e.g. genetics). In addition, injury data from many fields demonstrate that numerous physical and psychological parameters affect injury rates.[14] Though there likely are multiple factors underlying the differences in ACL injury rates in male and female athletes, neuromuscular control may play an important role in injury risk and is the most modifiable factor. While the prevention and treatment focus should remain in areas that are modifiable, investigations should continue into the relative contribution of less modifiable factors. This is especially important in the pubescent female athlete, where significant developmental changes occur both anatomically and hormonally. The epidemiologic data indicate that the changes that occur as a female athlete moves through puberty may lead to higher injury rates in this vulnerable, high-risk population. The neuromusculoskeletal changes that can alter both passive joint laxity and decrease dynamic joint stability could be modified if interventions were instituted at the right time.

Neuromuscular training in females has been shown to increase active knee stabilization in the laboratory and decrease the incidence of ACL injury, on the court or field in athletic female populations.[5-6, 74-75] Neuromuscular training facilitates neuromuscular adaptations that teach athletes to utilize joint stabilization patterns that employ safer muscular pre- and mid stance activation patterns (Figure 5). This training allows female athletes to adopt muscular recruitment strategies that decrease joint motion and protect the ACL from high, potentially injurious impulse loads sustained during athletic performance.[74, 76-77] However, more clear identification of the modifiable mechanisms would increase the potential for both screening for high risk athletes and targeting interventions to address the specific mechanisms that increase ACL injury risk in female athletes.

Increased dynamic valgus position and abduction loads in the lower extremity successfully predict increased risk of ACL injury in female athletes. These loads are often driven by dysfunction of the core or trunk, as well as loss of symmetry between limbs. The tuck jump assessment has been presented as one field-based method to assess risk for ACL injury by assessing the four neuromuscular imbalances during a functional task. The authors are currently developing additional field-based assessments using 2-D camcorder-based methods to develop simple yet objective measures to monitor multiple facets of neuromuscular control in female athletes. Using coupled biomechanical-epidemiological approaches, high-risk female athletes can be identified and be directed to engage in effective, targeted interventions to prevent ACL injury.

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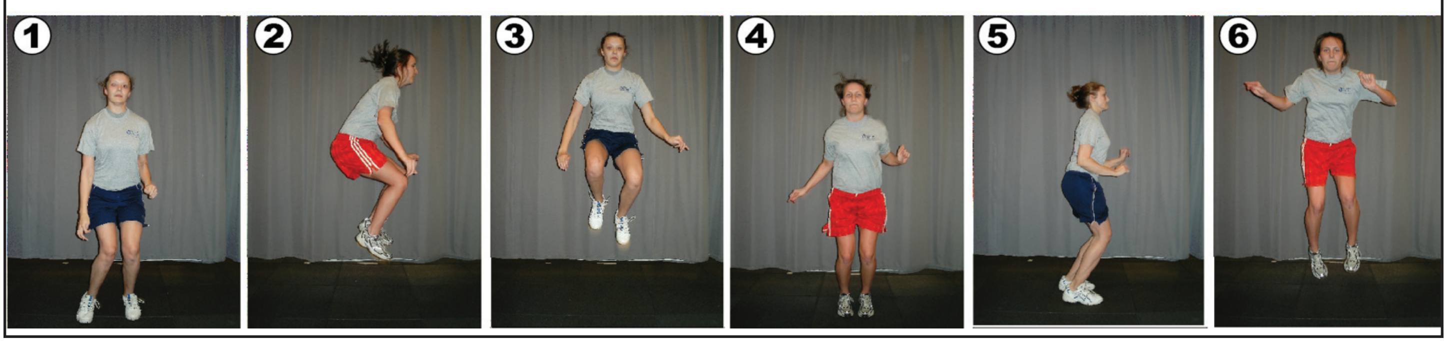
Appendix 1. *The Tuck Jump Assessment, criteria 1-6 are pictured below. Score any deviations from correct performance before, during, and after the performance of several tuck jumps over 10 seconds. More checked boxes indicates poorer technique, and also suggests the areas upon which the athlete should concentrate during training.*

Tuck Jump Assessment	Pre	Mid	Post	Comments
Knee and Thigh Motion				
① Lower extremity valgus at landing	☐	☐	☐	
② Thighs do not reach parallel (peak of jump)	☐	☐	☐	
③ Thighs not equal side-to-side (during flight)	☐	☐	☐	
Foot Position During Landing				
④ Foot placement not shoulder width apart	☐	☐	☐	
⑤ Foot placement not parallel (front to back)	☐	☐	☐	
⑥ Foot contact timing not equal	☐	☐	☐	
7. Excessive landing contact noise	☐	☐	☐	
Plyometric Technique				
8. Pause between jumps	☐	☐	☐	
9. Technique declines prior to 10 seconds	☐	☐	☐	
10. Does not land in same footprint (excessive in-flight motion)	☐	☐	☐	
	Total ______	Total ______	Total ______	



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