Avoiding the Failed ACL: How to Prevent ACL Tears Before They Occur

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Injuries to the anterior cruciate ligament (ACL) are common throughout the athletic population starting as young as 6 years old. These injuries occur from either traumatic, contact injuries or non-contact mechanisms (jumping or pivoting) during sport participation. Females are plagued by a 4–6 times higher incidence in non-contact injuries [1, 2]. There has been a large amount of research completed over the years regarding surgical techniques and rehabilitation after surgery, but prevention has been studied less. This chapter will review common causes for ACL injuries, discuss gender differences, introduce assessment for injury risk, and highlight the importance of different training components (strengthening, flexibility, plyometrics, proprioception/neuromuscular, and sport-specific training) to assist in ACL injury prevention.

Rationale for Prevention

The concept of ACL injury prevention was initially controversial. However, over the past 10 years, a significant body of research has emerged to demonstrate that prevention programs clearly decrease the number of ACL tears. An analysis of seven studies of ACL injury prevention programs that were conducted between 1999 and 2008 evaluating over 12,000 athletes found that, on average, participation in a prevention program reduced the risk of non-contact ACL injury by 71 % [3].

In addition to reducing ACL injuries, prevention programs can also reduce other knee injuries as well as ankle and overuse injuries [4]. However, the programs must be done by the athletes throughout the season in order to have the effect. This requires a coordinated effort on behalf of the athletes, the coaches, and the team managers.

Extrinsic Versus Intrinsic Risk Factors

Risk factors for ACL injury may fall into two categories: extrinsic factors or intrinsic factors. Intrinsic factors are specific to the individual and may include: anatomical differences, hormonal changes, neuromuscular risk factors, and gender. Extrinsic factors vary from person to person and include: level and type of competition, footwear and field surface, and weather conditions [5].

The ACL has been found to have receptor sites for sex hormones (estrogen, testosterone, and relaxin). Also, the use of oral contraceptives and hormone fluctuations during follicular and ovulatory phases of the menstrual cycle may affect ACL susceptibility to injury. Overall, further research is needed to help better understand the

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female hormonal changes throughout the menstrual cycle and how they can affect the neuromuscular system with relation to athletic participation [5, 6].

Gender difference will be discussed throughout the research presented in this chapter. Overall sex differences play a role in knee kinematics and movement patterns. Women have been shown to demonstrate a greater knee abduction moment at initial contact and decreased peak stance internal rotation of the knee when compared to men. In addition, looking at recreational athletes may disguise sex-based tendencies due to variations in neuromuscular control and muscular strength [7].

Anatomical variations include notch size and posterior tibial slope. Bilateral ACL injuries may result from having a smaller notch width. ACL size tends to be smaller in females which may predispose them to less linear stiffness, a lower load to failure, and lack of energy absorption [5]. Potential injury may also occur due to association of general joint laxity, femur length, and posterior tibial slope and anterior tibial translation that can result in increased stress on the ACL [5, 6].

Neuromuscular control is the only intrinsic condition that the athlete and therapist may be able to change. The ACL is affected by anterior shear forces which can be coupled with coronal and axial plane forces. Anterior shear forces vary depending on the amount of quadriceps activation and degree of knee flexion the athlete displays with landing and movement changes. As knee flexion angles move less than 30°, there is an increased anterior shear force provided by the quadriceps and less co-activation of hamstrings, allowing for increased injury risk [5].

Neuromuscular differences occur between female and male athletes throughout stages of development. Evidence shows that the numbers of ligament strains are relatively equal in boys and girls before adolescence, but girls' rates will increase following a growth spurt spanning into maturity [6]. Girls between ages 12–16 demonstrate landing postures with increased knee extension and valgus (knock-knees) stress throughout stance. Females generally have an increase in knee joint laxity, genu-recurvatum, and less resistance to tibial rotation which can allow for injury in the sagittal, frontal, or transverse planes of motion. Males, on the other hand, demonstrate neuromuscular changes after growth spurts. This separates the males from the females as they will demonstrate development in power, strength, and coordination. This can be seen in improved scores of vertical jump height in male vs. female adolescent population [6]. Males and females will be affected equally by fatigue during athletic participation. As fatigue increases, the dynamic stability and timing of motion response to stimulus decrease, leaving the ACL susceptible to increased anterior shear forces and injury [5].

Extrinsic risk factors will also influence the risk of ACL injury, but athletes may have more control over them. Level of competition has demonstrated an increase in ACL injuries during game time situations compared to practice setting. Footwear and surface friction is necessary for stability, but too much friction may cause catching or stopping of the foot unintentionally. Torsional resistance can be altered when a football athlete wears shoes with more cleats or a handball player changes surfaces from artificial to wood flooring. Weather conditions will increase susceptibility of ACL injury with causing variations in footwear-surface interface. Protective (prophylactic) bracing has been used in skiers, military cadets, and football athletes, but no significant difference has been demonstrated [5].

Neuromuscular Imbalances

Females demonstrate sex-related neuromuscular imbalances: ligament dominance, quadriceps dominance, leg dominance, and trunk dominance. Neuromuscular imbalances may demonstrate differences in muscular strength, power, or activation patterns which may lead to increased joint and ligament loads on the knee [6].

Ligament Dominance

Ligament dominance can be defined as an imbalance between neuromuscular and ligamentous control of dynamic knee stability. This results in the ligament instead of lower extremity musculature absorbing ground reaction forces during sport. Lack of control is demonstrated in the frontal plane with landing and cutting movements, such as single-leg landing, pivoting, and deceleration. Valgus stress is produced when the athlete demonstrates poor trunk control. The ground reaction forces follow trunk motion and will shift the athlete's center of mass laterally to the center of the knee resulting in dynamic valgus positioning. Addressing the posterior chain (gluteals, hamstrings, and gastroc-soleus complex) will provide proper recruitment to obey Newton's third law (obeying equal and opposite reaction forces) [2, 6].

Quadriceps Dominance

Quadriceps dominance is an imbalance between recruitment of quadriceps and hamstrings [2]. Increased injury risk is shown with landing and cutting at low knee flexion angles (<30°). Knee flexion less than 30° has demonstrated increased quadriceps anterior pull on the tibia and less co-contraction of the hamstring and gastrocnemius, resulting in additional strain on the ACL [2]. The hamstrings will provide a synergistic motion and pull the tibia posteriorly to decrease stress on the ACL. During landing, the hamstring and gastrocnemius activate to generate an equal and opposite torque to prevent excessive forward movement of the athlete's center of mass. When the center of mass is too far forward, the knee will extend and will be enhanced by the GRF. Previous research has demonstrated that males, unlike females, activate their hamstrings first when landing. Women activate quadriceps first and display lower knee flexion angles with landing, resulting in an increased risk of ACL injury [8].

Leg Dominance

Leg dominance can be defined as an imbalance from side to side. There are deficits in regard to muscular strength, flexibility, and coordination [2, 6]. This deficiency presents a risk for both lower extremities. The athlete can become over reliant on the dominant leg, therefore adding increased stress and torque on that knee. The non-dominant or weaker limb is at risk due to the inability of load absorption to meet the demands of the sport by the surrounding musculature [2].

Trunk Dominance

Trunk dominance occurs more often in women than in men. This deficit is seen when an athlete is unable to control his or her center of mass which may be related to growth and maturation. A female's center of mass is located higher from the ground and the distribution of body mass and percentage of body fat is greater in women [8]. With decreased ability to control trunk motions and control perturbations, the athlete will respond with excessive frontal plane trunk motion. This increase in GRF and valgus force subjects the knee to increased injury risk [6]. Research has shown women respond better when treatment focuses on dynamic trunk training. Men demonstrate improvement in trunk control with single-leg balance and wobble board balance programs [8].

Building a Foundation for Prevention

In 1999, Hewett et al. proposed a three phase jump training program:

Phase I: Techniques Phase: focus on correction of posture, maintain vertical motion of jump, soft-landing, and instant recoil for next jump [2]

Phase II: Fundamental Phase: building strength, power, and agility

Phase III: Performance Phase: achievement of maximal vertical jump height

Hewett found that neuromuscular training can elicit biomechanical effects including reduction of landing forces, reduction of abduction-adduction moments, and increased hamstring-quadricep ratios. Improving posterior chain strength will contribute to improved control in the coronal plane, therefore demonstrating a reduction in valgus stress. Improving hamstring activation is crucial to diminish increased anterior shear on the knee as women tend to be quadriceps dominant. The hamstring provides important stabilization to the knee and should not be neglected. As a result of this program, women demonstrated hamstring to quadricep ratios at comparable levels to men [9].

Caraffa et al. [10], in 1996, looked at prevention of ACL injuries in soccer players. She utilized a preseason (30 day) training program for 20 min daily consisting of five phases:

1. Single-leg stance 2.5 min (4 trials per day)
2. Single-leg stance on rectangular balance board
3. Single-leg stance on round board
4. Single-leg stance on a combined round and rectangular board
5. Single-leg stance on BAPS board (multiplanar)

This program was reduced in frequency to 3× per week minimum during the soccer season. As a result the proprioceptively trained group saw a reduction sevenfold over the control group (70 arthroscopically confirmed ACL tears in the control group compared to only 10 in the trained group) [10].

In 2003, Myklebust et al. looked at a span of three seasons on prevention programs for ACL injury in female team handball. The program was completed 3× per week for a duration of 5–7 weeks during preseason, and 1× per week during season. The program focused on understanding and demonstrating quality movements, core stabilization, and proper hip and knee position with running, cutting, and jumping motions. Each week the athlete was progressed with more challenging exercises in each domain. In the end, neuromuscular training programs work best when athletes are motivated and younger. Younger athletes demonstrate a lack of preestablished movements and can easily be educated and trained with proper technique in which to build on that foundation [11].

Myer et al. [2] in 2004, reported on three essential components of broad training program:

1. Dynamic: educate on correct biomechanical movements utilizing a controlled environment for high-risk, sport-specific maneuvers
2. Neuromuscular: improvement in development of joint stabilization and muscle pre-activation to reduce high impact loads on the knee
3. Analysis: educate the athlete with feedback (visual and verbal) during and after task completion

It is important to remember that quality of movement must be maintained as quantity of repetitions is increased for successful training outcomes [2].

Ligament Dominance: Identification

Utilization of a 31-in box-drop test with maximal vertical leap can help identify an athlete as "ligament dominant." The athlete will show knee adduction during landing and low knee flexion angles which sets up the athlete for injury. The athlete must be made aware of the dangerous positions that they display as well as education in proper technique. Having the athlete visually see her technique flaws with the use of a mirror will make the athlete aware of errors in task completion. It is also important to have the coach utilize proper terminology and consistent cues when giving feedback during specific timing (during jump or landing) of the exercise. Sample feedback phrases may be "on your toes" during the jump phase and "knees bent" during landing [2] (Fig. 2.1).

Ligament Dominance: Treatment

First the athlete should be educated in proper athletic ready position: knees bent, shoulders back, eyes looking straight ahead, body weight on the balls of the feet (knees never over toes), and feet shoulder-width apart (Fig. 2.2). Simple wall-

Fig. 2.1 Vertical jumps. (**a**) Landing phase. (**b**) Jump phase. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.2 Athletic ready position. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

jump exercises can be taught with increasing intensity of jumps. It is important for the athlete to keep knees apart with landing which reduces loading of the ACL and increases knee flexion. Progression from wall jumps to the tuck jump will allow for analysis of coronal plane movements. Utilization of the broad jump with 3–5 s holds advances the athlete in gaining and maintaining dynamic stability. To assess transverse plane motion, 180° jump can be used which teaches dynamic trunk and lower extremity control as forces are absorbed and immediately redirected in opposite motion [2].

After mastering double-leg jumps and lands, it is time to progress to single-limb hop-and-hold exercises. This motion is comparable to mechanisms that cause non-contact ACL injuries. As the athlete improves, she will be advised to land with deeper knee flexion. Finally drills involving unanticipated cutting (Fig. 2.3) are important since valgus loads are doubled with these motions. Teaching and practicing these skills may carry over to real-time game situations as they become a learned movement response [2].

Fig. 2.3 Running and cutting. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Quadriceps Dominance: Identification

Quadriceps dominance can be defined as an imbalance between strength, recruitment, and coordination of quadriceps and hamstrings [6]. Hamstring to quadriceps isokinetic strength ratio <55–60 % indicates quadriceps dominance. Another test that may indicate quadriceps dominance is single-leg hop-and-hold in deep squat (>90°). If the athlete is unable to maintain deep flexion or maintain upright posture, there may be less than optimal hamstring firing [2].

Quadriceps Dominance: Treatment

It is important to address strengthening of the posterior chain (gluteals, hamstring, and gastrocnemius) to prevent improper, low flexion angle form instance, landing and cutting [8]. Drills using squat jumps and broad jump and hold assist in hamstring co-contraction training for stabilization in static positions [2]. Also exercises such as plyometric 90/90 squat jumps (Fig. 2.4a, b), Russian hamstring curls (resistance band around trunk for concentric and eccentric loading), ball bridge curls (double- to single-leg progression) and plank are appropriate for activation of hamstring and abdominal stability [8] (Fig. 2.5a, b).

Carcia et al. [12] noted a gait deviation called "gluteus maximus lurch" in which there is significant gluteus maximus weakness. This deviation demonstrates increased trunk extension at heel-strike and center of mass moves posterior to the hip. This will cause inhibition of gluteus maximus, minimizing hip extension activation [12].

Activation of gluteus medius and maximus is important to diminish hip internal rotation and adduction during landing, and overall knee valgus loading forces. Suggested exercises to improve gluteal function were side-lying clam, side-lying hip abduction, single-limb squat, single-limb dead-lift, lateral band walks, multiplanar lunges (Fig. 2.6), and multiplanar hops. The gluteus medius functions concentrically to abduct the hip, eccentrically to control hip adduction and internal rotation, and acts to stabilize the pelvis. Ideal gluteus medius exercises included sidelying hip abduction, single-limb squats (Fig. 2.7), lateral band walk, single-limb deadlift, and single-limb side hop (Fig. 2.8). Gluteus maximus was shown to have the highest activation with the transverse plane lunge, single-limb squat, and single-limb deadlift [13].

Leg Dominance: Identification

Leg dominance is a neuromuscular imbalance indicated by asymmetrical strength or power (difference of 20 % or more) between limbs. This may be assessed by performance of single-limb stance on an unstable platform allowing postural sway to be calculated. Another way to assess leg dominance is by utilization of single-limb hops, where an athlete hops into different quadrants [2].

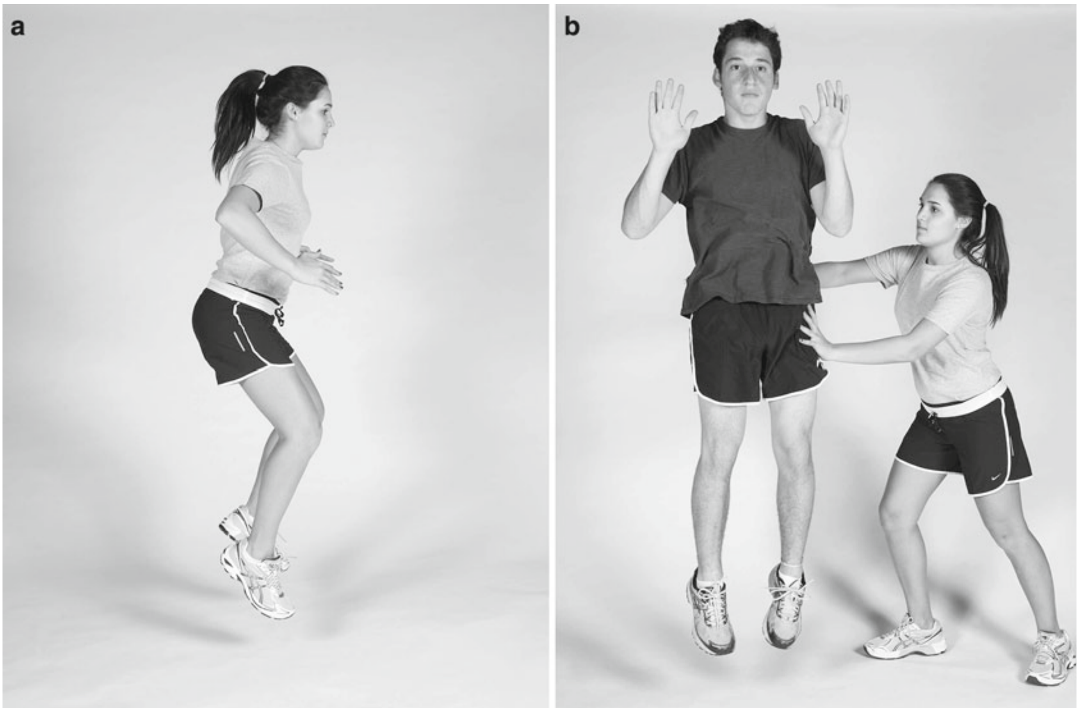

Fig. 2.4 (**a**) Box jumps (side-to-side, front-to-back, and along both diagonals). (**b**) Box jumps with Partner's push. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.5 (**a**) Thirty second plank. (**b**) Thirty second plank with one leg lift. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.6 Walking lunges. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Leg Dominance: Treatment

When addressing leg dominance deficits, it is important to start activities with double-leg

Fig. 2.7 One-leg squats on wobble-board. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

Fig. 2.8 Lateral jumps. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

before single-leg activity. It is important to maintain equal strength, balance, and foot placement between legs. For example, allowing one leg to land posterior will foster poor and unsafe habits when landing from a double-leg hop. Single-leg exercises, such as hop-and-hold or single-limb balance on unstable surfaces can help address improper landing or overuse of dominant leg. Bounding will assist in learning movement in multiplanar directions and achieve maximal vertical height and horizontal distance with each repetition [2]. When both lower extremities are alternately used in single-limb activities, there is a cross-over effect. Single-limb hopping may also influence recruitment of the posterior chain musculature, therefore assisting in reduction of quadriceps dominance as well.

Trunk Dominance: Identification

The most difficult imbalance to detect is trunk dominance during dynamic function. Performing a ball bridge with hamstring curl may assist in identifying pelvic instability by demonstrating rotation or anterior/posterior (AP) pelvic tilt during task completion in the transverse and frontal planes. Assessment of hip external rotation strength may also be a good predictor of future injury since that acts as a main stabilizer of the core and lower extremities [8].

Trunk Dominance: Treatment

It is important that the focus is not directed to the rectus abdominus, but rather to the deep

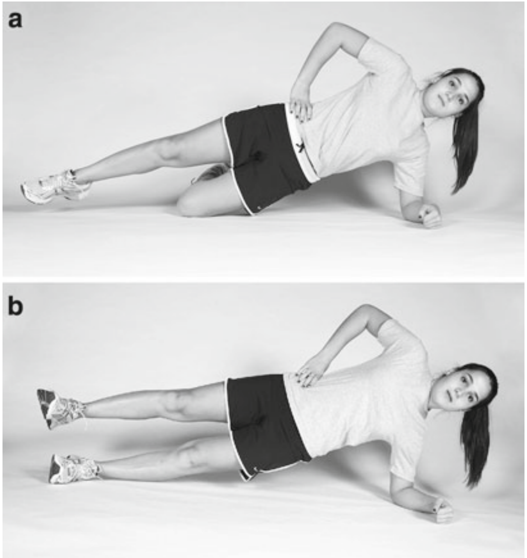

Fig. 2.9 (**a**) Side plank static. (**b**) Side plank with leg lift. Reproduced with permission from "The ACL Solution: Prevention and Recovery for Sports' Most Devastating Knee Injury". Marx, Myklebust & Boyle, Demos Publishing 2012

musculature of the core: transverse abdominus and multifidus. One way to address rotational hip strength in a closed kinetic chain is by using a resistance band to work concentric and eccentric rotational motion while on one leg. This rotational motion is an example of pelvic rotation on the femur. It is important to cue the patient and provide appropriate feedback to prevent pelvic drop in the frontal plane or pelvic tilting in the sagittal plane [12].

Leetun et al. [14] in 2004 hypothesized that lack of core stability contributes to lower extremity injuries in females. They looked at the quadratus lumborum as a lumbar stabilizer and hip abduction and external rotation strength to assist in maintaining a level pelvis and prevention of hip adduction and internal rotation while in single-limb stance. When testing for endurance in side plank (Fig. 2.9a, b), women showed a lack of endurance along with reduced hip abduction and external rotation isometric strength. When the hip and trunk are weak, females may be susceptible to large external forces during athletic participation. It is important to build endurance and train stabilizing pelvic musculature to assist in appropriate weight transfers and maintaining proper center of mass with motion involving cutting, jumping, and single-limb loading [14].

How Can We Assess for Potential Injury?

Development of a screening tool for injury risk is important to utilize before season. This tool should be simple to carry out and require dynamic movement rather than static testing. If coaches can see the deficits during preseason, they will be more inclined to complete a prevention program to specifically address the individual deficits. This screening tool should also be utilized for reassessment to monitor an athlete's progress [8].

The tuck jump is a "clinician-friendly" field-based tool that incorporates limb symmetry, core stability, posterior chain muscle firing, and control of both lower extremities in the sagittal plane [8]. Quality of motion during a 10-s trial of consecutive jumps is used to assess technique. During flight and at landing, the clinician should observe for the following movement flaws to determine which dominance the athlete displays (see Table 2.1) [8, 15].

Neuromuscular Training

An important part of athlete education for proper movement patterns is neuromuscular training. Athletes can learn how to utilize safer joint stabilization patterns and muscular pre-activation pat-

Table 2.1 Movement flaws in jump training

Dominance	During flight/jump	At landing
Ligament dominance	N/A	Valgus at landing Foot placement > shoulder width apart
Quadriceps dominance	N/A	Excessive landing noise
Leg dominance	Thigh not side to side (during motion and peak height)	Pause between jumps Does not land in same footprint
Trunk dominance	Thighs do not reach parallel (at peak height)	Pause between jumps Does not land in same footprint

terns to decrease the potential danger to the ACL during isolated sport-specific motions [8]. Research has shown that females are at greater risk while participating in sports such as soccer and basketball. Both sports require typical movement patterns of jumping/landing and cutting which are classic non-contact mechanisms of ACL injury.

Paterno [1], in 2004, observed restoring dynamic functional control through postural stability. Assessment of stability measures in the anterior/posterior (AP), medial/lateral (ML), and total overall postural stability were assessed. He chose a 6-week dynamic neuromuscular training program including:

1. Balance training and hip/trunk/pelvis strengthening (to improve strength, stability, and coordination to assist in redirecting forces)
2. Plyometrics and dynamic movement patterns (progression of jumping, pivoting, and cutting along with advancements from double-limb to single-limb)
3. Resistance training (improve strength throughout full range of motion to compliment balance and plyometric advancements)

These subjects received constructive feedback from coaches during and after technique. Overall, improvements were seen in AP and total postural stability, but no significant improvement in ML (coronal plane). This supports findings that valgus stress is a risk factor for female athletes compared to males [1].

In 2005, Hewett et al. [16] studied biomechanical measures of neuromuscular control and valgus loading at the knee as a predictor of ACL injury in female athletes. ACL injuries occur frequently due to high external joint loading during deceleration, lateral pivoting, and landing during sports. Increased valgus stress will correlate to lack of neuromuscular control in the coronal plane. This may result from insufficient adaptations of adductors and hip flexors (ligament dominance) and poor hamstring strength (quadriceps dominance). His results demonstrated that neuromuscular training programs not only can help reduce GRF and valgus stress, but also resulted in an increase in muscular power within 6 weeks [16].

Myer et al. [17] in 2006 compared the effect of plyometric and dynamic stabilization/balance training on lower extremity biomechanics. Prior research has shown that plyometric training alone may not produce beneficial results for female athletes. Female athletes demonstrate primary coronal plane movement strategies to control knee movement, which has been proven to be unproductive for proper force dissipation. It is believed that a combination of plyometric and dynamic balance training will decrease valgus loading, contralateral limb asymmetries, and impact forces. Results showed female athletes had improved sagittal plane control eliminating reliance on insufficient coronal plane movements and therefore reducing injury risk [17].

Cowley et al. [18] in 2006 examined the differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. Movement strategies including drop vertical jump in basketball and cutting in soccer demonstrated an increase in GRF and a decrease in stance time. Cutting activities compared to sagittal plane running may double the valgus load on the knee. Demonstration of valgus stress during a sport-specific motion indicates that the athlete lacks control of GRF, therefore placing the ligament at risk for injury. The authors also noted limb asymmetry between tasks completed in both basketball and soccer. Basketball placed increased GRF on the non-dominant limb with drop vertical jump, and cutting motions in both soccer and basketball placed increased GRF on the dominant leg. These factors indicate the need to train these athletes differently to meet the demands of the sport. For example, training basketball athletes with depth jumping to focus on landing forces and valgus knee collapse, where soccer athletes may focus on minimizing valgus loading with unanticipated cutting drills [18].

Myer et al. [19] in 2005 studied how a neuromuscular training program improved performance and lower extremity biomechanics in female athletes. Participants underwent a 6-week progressive program consisting of plyometrics, resistance training, core and balance training, and speed training. After completion of the program, the trained individuals demonstrated significant increases in vertical jump, single-hop distance, speed, squat, and varus-valgus stress compared to untrained subjects. The authors determined that preseason and in-season program combining all training components was indicated [19].

When and How Do We Start Prevention Programs?

The ideal age to initiate prevention training programs to improve neuromuscular and biomechanical risk factors is unknown. Benjaminse and Otten [20] reports that age 6–12 may develop correct playing techniques and allows time for these learned movements to become automatic. Between ages 12 and 14, athletes may begin prevention programs to enhance body awareness during skilled movements. Myer et al. [6] found 12 years of age would correlate to 88 % of adult stature. They determined that prevention training programs should be implemented for females before the growth spurt during adolescence.

Motor learning for athletes has been studied. Implicit learning has been shown to be effective in allowing the brain and body to establish conditions where performance ability is greatest. Explicit learning was shown to be less efficient due to the complexity of sport requiring attention not only to the movement of the LE but also to the movement of the ball and opponent [20].

Visual and verbal cues are also important learning factors. Visualization of a task through the use of mirror or reviewing videotape of the athlete's performance is a tool used for implicit learning. This allows the athlete to view themselves completing a motion correctly or improperly with self-correction. The athlete will learn how to problem-solve and develop a solution that best fits the individual's body motion [20]. Verbal cues have also been shown as positive factors during task completion to allow the athlete to correct incorrect joint angles [21].

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