Rationale and Implementation of Anterior Cruciate Ligament Injury Prevention Warm-Up Programs in Female Athletes

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Abstract

Bien, DP. Rationale and implementation of anterior cruciate ligament injury prevention warm-up programs in female athletes. *J Strength Cond Res* 25(1): 271–285, 2011—The sex disparity in anterior cruciate ligament (ACL) injury risk and the subsequent adverse effects on knee joint health, psychosocial well-being, and financial costs incurred have produced a surge in research on risk factors and interventions designed to decrease this disparity and overall incidence. Biomechanical and neuromuscular differences have been identified throughout the trunk and lower extremity that may increase noncontact ACL injury risk in female athletes. Evidence demonstrates that many risk factors are modifiable with intervention programs and that athletic performance measures can be enhanced. No universally accepted ACL injury prevention program currently exists, and injury prevention programs are diverse. Anterior cruciate ligament injury prevention programs introduced in a warm-up format offer multiple benefits, primarily, improved compliance based on improved practicality of implementation. However, drawbacks of warm-up style formats also exist, most notably that a lack of equipment and resources may preclude measurable improvements in athletic performance that foster improved compliance among participants. The purpose of this review is to analyze the current literature researching possible biomechanical and neuromuscular risk factors in noncontact ACL injury in female athletes and the most effective means of implementing critical elements of a program to decrease ACL injury risk in female athletes while improving athletic performance. Hip and hamstring training, core stabilization, plyometrics, balance, agility, neuromuscular training with video and verbal feedback to modify technique, and stretching appear to be essential components of these programs. Further research is critical to determine ideal training program volume, intensity, duration, and frequency.

Key Words knee, training, neuromuscular, women

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Introduction

High-school and collegiate age women are 3–4 times more likely to suffer anterior cruciate ligament (ACL) injuries than do men competing in the same sports (1). A growing body of evidence stemming from long-term follow-up studies indicates that ACL injury increases risk for secondary injury such as meniscal tears, and osteoarthritis, which occurs at a greater rate in individuals with ACL-deficient and ACL-reconstructed knees (3,35,68). These biological consequences of ACL injury, the financial implications of management of ACL injury for surgery and rehabilitation of ACL reconstruction (109), and psychosocial costs, such as loss of time in sport participation and decreased academic achievement, have spurred the recent advancement of ACL injury prevention programs (54). Many of these programs have been introduced in a warm-up style format (Table 1) and successfully decreased noncontact ACL injury risk, but many of these published studies using a warm-up format have been hampered by poor methodological quality (40,51,100,117,119). Some of these methodological errors include the following: limited number of subjects, high subject drop-out rates limiting statistical power of results, failure to differentiate between contact and noncontact ACL injury rate, failure to accurately determine exposure time of subjects, and poor subject compliance. Despite these errors, ACL injury prevention programs appear to show significant promise in limiting noncontact ACL injury incidence in female athletes.

Advantages of ACL injury prevention programs in a warm-up format are minimal time requirements and improved practicality because they are cost effective and can be performed on-field with minimal equipment needs. These factors may foster improved compliance of program adherence among coaches and participants and affect statistical outcomes (3). Another potential benefit of a warm-up format is the avoidance of increased fatigue,

Table 1. Summary of existing ACL injury prevention warm-up programs in female athletes.*

Reference	Subjects	Training program components	Program format	Results	Notes
Gilchrist et al. (39)	1,435 collegiate female soccer players: 853 control athletes, 583 intervention	PEP: stretching, strengthening, plyometrics, agility training, video education	Daily, on-field, in-season 12-week program	70% decrease in noncontact ACL injury in intervention group vs. controls	Coaches/ATCs monitored and supplied verbal feedback, unable to fully control fidelity and use of program in intervention and control groups, unable to fully control practice drills not included in PEP program
Mandelbaum et al. (70)	5,703 female amateur soccer players ages 14–18: 3,818 controls, 1,885 intervention group	PEP: stretching, strengthening, plyometrics, agility training, video education	20 mins/session, 2–3× per week, sport-specific on-field warm-up	88 and 74% reduction on ACL injury in first 2 seasons, respectively	Results may have been biased by voluntary enrollment, nonrandomized. Participants were educated by videotape and monitored only by coaches
Myklebust et al. (88)	Female team handball players: control season (942 players), first intervention season (855 players), second intervention season (850 players)	Balance, proprioception, plyometrics, agility training	15 mins, 3× per wk × 5–7 wk. Preseason, 1× per wk in-season	Limited extraction and interpretation of data because of design and implementation flaws	Nonrandomized, insufficient statistical power, injury and program technique monitoring performed by coaches, results hampered by low compliance levels amongst participants. Statistically significant decrease in ACL injury rate in intervention group.
Petersen et al. (100)	Female team handball players: 134 intervention, 142 control subjects	Balance, proprioception, plyometrics	N/A	ACL injury per 1,000 athletes: Control group 0.21, intervention group 0.04	Limited number of subjects
Soderman et al. (117)	221 semiprofessional and professional female soccer players (100 control, 121 intervention group)	Balance, proprioception training	10–15 mins per session, 3× per wk, over 7 months	No significant difference between groups in lower extremity injury frequency or type	Single component program, affected by drop-out rate, no differentiation of contact vs. noncontact ACL injury
Soligard et al. (118)	1,892 female soccer players, ages 13–17 (y)	Core stability, balance, proprioception, strengthening, agility, plyometrics, stretching	20 min daily in-season, on-field, warm-up	ACL injury specifics not provided, injury categorized by body category and acute vs. overuse	Intervention group had significant decrease in severe injury, overuse injury, and overall injuries. However, reduction in lower extremity injury did not reach statistical significance
Steffen et al. (119)	2,092 female youth soccer players (1,001 control, 1,091 intervention group)	Core stability, lower extremity strength, agility, balance	15 min, in-season warm-up over 8 months	No differences between groups in overall or specific injury rates	Poor program compliance hampered results. Only 14 of 58 intervention teams completed >20 training sessions

*PEP = prevent injury and enhance performance; ACL = anterior cruciate ligament.

which has been identified as a potential factor in the lack of success in injury prevention programs that were performed posttraining session and also found to negatively impact biomechanics during athletic tasks that may increase injury risk susceptibility (3,101,120).

A drawback of ACL injury prevention programs that use a warm-up format is that the lack of high-intensity overload in these programs may preclude measurable athletic performance enhancement effects (i.e., improved vertical jump, speed, etc.) (3). A recent review of injury prevention and performance enhancement programs by Alentorn-Geli et al. found that training targeted toward improving measures of performance result in better compliance ranging from 80 to 90% (3). Other drawbacks of ACL injury prevention warm-up vs. more traditional warm-up formats may include the following: detrimental effects on skill performance because of increased fatigue, increased time demands, which may limit sport-specific skill training and subsequent program adherence by coaches, and decreased ability to modify warm-up components to create variable challenges and athletic demands and limit participant disinterest because of monotony.

A review of the current evidence is necessary to understand the most effective means to develop warm-up programs to target and efficiently address risk factors predisposing female athletes to noncontact ACL injury, while striving to achieve physical performance gains. Recent studies provide evidence that warm-up format ACL injury prevention programs are capable of providing improvements in athletic and physical performance measures, and effecting biomechanical changes (63,65,103). Improved physical performance measures provide positive psychological reinforcement, which may allow improved compliance from female athletes and coaches to ACL injury prevention programs.

Injury Mechanism

Approximately 70% of ACL injuries are noncontact in nature (76). To prevent noncontact ACL injuries in female athletes, it is critical to understand the mechanisms that cause these injuries. Shimokochi et al. found multiplane (sagittal, frontal, and transverse) knee loadings were the primary mechanism in a recent review of various research methods studying noncontact ACL injury mechanisms, with the highest ACL loads incurred during a knee valgus load combined with knee internal rotation and quadriceps force application with insufficient hamstrings cocontraction at or near full knee extension (114). These findings were reinforced in separate retrospective video analyses of ACL injuries, which proposed evidence that support 2 predominant loading patterns: (a) anterior tibial shear and (b) injury as a result of "knee valgus collapse" (defined as a combination of knee valgus, hip internal rotation, and tibial external rotation) near full extension and foot planted during deceleration (8,9,109).

Anterior tibial shear, specifically at knee flexion angles around 20–30° (0° defined as full knee extension), is often identified as a contributing factor to ACL injury mechanisms (2). However, several authors have reported that isolated sagittal plane forces are not high enough to tear the ACL during sports (2). Cadaveric studies indicate that a combination of forces, specifically with increased knee valgus loads, directly elicit higher strain on the ACL than isolated motions and torques (2,67,71,82,124). These force combinations are consistent with the multiplane loading injury mechanism findings of Shimokochi et al. and sufficient to trigger ACL tearing (2,67,71,82,124).

These force combinations most commonly occur during athletic tasks involving deceleration, change of direction, and jump landings. Biomechanical and neuromuscular differences at the trunk and lower extremities during these sport tasks are believed to be the most likely factors to account for the significant bias in noncontact ACL injury rates in women vs. men (41).

Hip and Knee Pathomechanics and Interventions

Proximal lower extremity neuromuscular control and postures at the hip and knee may be a significant factor in ACL injury risk in women. Female athletes exhibit greater hip adduction and internal rotation with decreased knee flexion during walking, running, anticipated and unanticipated cutting, and landing (36,54,103,115). Increased hip adduction and internal rotation predispose a woman to increased knee valgus vs. men (36,103). Recent video analyses also revealed that women had higher knee valgus angles than men did during noncontact ACL injuries, and that dynamic valgus was the most common ACL injury mechanism in female handball and basketball athletes (9,62,91). A prospective study by Hewett et al. showed that women who tore their ACL in-season demonstrated knee valgus moments 2.5 times that of those who did not suffer ACL injury during jump landings. They identified that knee valgus angles and moments were the primary predictors of ACL injury risk in female athletes (45).

Borotikar et al. also found that fatigue-induced increases in peak knee abduction or valgus angle and hip rotation at initial contact were significantly more pronounced during unanticipated compared to anticipated single-leg landings in women (11). This suggests that increased fatigue and unexpected perturbations may further increase female ACL injury risk through increased knee valgus postures.

Insufficient neuromuscular control in female athletes at a higher risk of developing noncontact ACL injury may be a factor in this increased dynamic knee valgus posture or "valgus collapse" identified by Myer et al (82). Wojtys et al. found that collegiate female athletes involved in high-risk sports exhibited less muscular protection of the knee ligaments during external torsional loading than did size and sport-matched male athletes (125). Women also activate the hip musculature differently than men do in response to sudden loading (48). Gluteus maximus and medius may play an increased role in mediating muscular protection and the control of hip adduction and femoral rotation in helping female athletes avoid these “at-risk” positions for ACL injury (88).

A weak gluteus medius may influence dynamic valgus collapse because of the inability of muscles to keep the hip abducted, especially during high demand single-leg weight-bearing activities such as landing, cutting, or changing direction (2). Zhang and Wang completed a study, which showed that active contraction of hip abductor and adductor muscles can increase knee joint stiffness by 58%, reinforcing the proposed role of gluteus medius (131). Correlations between hip abductor strength and landing kinematics are larger for women than for men, and hip external rotator strength has also been identified as a predictor of lower extremity injury and frontal-plane deviation with single-leg squatting (56).

Gluteus maximus has an important role as the most powerful hip external rotator, and hip external rotation strength has been found to be a reliable predictor for lower extremity injury risk (63,89). Zazulak et al. found decreased gluteus maximus activity in women during single-leg landings, which could lead to increased femoral internal rotation and subsequently increased knee valgus postures (128). The ability to assist in control of dynamic valgus collapse at the knee makes addressing gluteus maximus and medius strength and control imperative in a training program for ACL injury prevention. Targeted training of the gluteus maximus and medius may assist in control and reduction of pathomechanical hip motions and postures placing the knee in at-risk position for ACL injury.

Mascal et al. demonstrated kinematic improvements in women in hip adduction and femoral rotation through a 14-week hip strengthening program (72). In recent electromyographic (EMG) studies, sidelying hip abduction and side planks (Figure 1) have demonstrated sufficient maximal voluntary isometric contraction (MVIC) (≥60%) to allow strengthening at gluteus medius, whereas single limb squats and single-leg deadlifts (Figures 2A, B) maximally elicited

Figure 1. Side plank or side bridge with progressions including hip abduction or use of unstable surfaces.

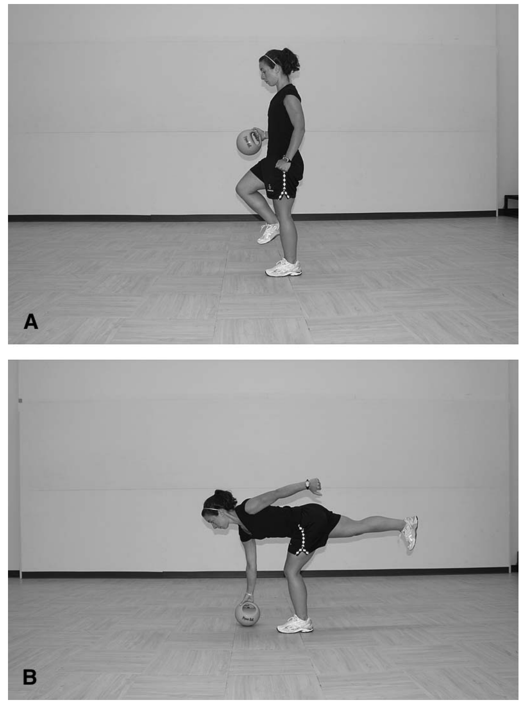

Figure 2. (A, B) Single-leg deadlift (SLDL) with the use of weighted balls or bands to increase resistance.

gluteus maximus (25,30). Dynamic single limb stance weight-bearing activities such as the single-leg squat also activated gluteus medius significantly better than double limb stance exercises did in a recent EMG study, suggesting the importance of inclusion of dynamic single-leg weight-bearing exercises (61). These hip exercises can be easily implemented in a warm-up style program using minimal equipment or partnered manual resistance to provide sufficient muscle overload for strengthening to improve control of dynamic valgus postures.

Hamstring Activation and Strength Deficits and Effective Interventions

Deficits in female athletes in hamstring activation and its role in control of dynamic valgus postures may also play a role in the disparity in ACL injury rate in women vs. men. Hamstring recruitment may provide dynamic knee stability by resisting anterior and lateral tibial translation and transverse tibial rotations (2). The medial and lateral hamstrings are selectively activated to control internal and external rotations of the tibia (64). A recent study by Zebis et al. confirmed that female athletes with reduced preactivation of the semitendinosus during side cutting were at increased risk for future ACL rupture (129). Uninjured women were shown to demonstrate increased medial hamstring preactivation during downhill walking and running tasks vs. the injured group (23). Less activation in the medial hamstrings vs. lateral hamstrings has also been observed during the loading or closed kinetic chain phase of a forward hop in female athletes (98). Medial hamstring musculature preactivation may be particularly important to limit excessive knee valgus and external rotation and subsequent ACL strain (3). McLean et al. confirmed that medial hamstring preactivation or premotor time, defined as time between stimulus presentation and initiation of muscle EMG burst, correlated with peak knee abduction load during unanticipated single-leg landings in female athletes. This confirms the increased critical role of medial hamstrings in dynamic knee stability motor strategies during athletic tasks and highlights the importance of targeted training at the medial hamstrings and neuromuscular training to improve feedforward motor programming during athletic tasks (73).

Although preactivation and motor planning appear essential to safe preparation for sport-specific maneuvers to limit noncontact ACL injury risk, active control at the hamstrings also appears critical. Wojtys et al demonstrated that female athletes had less active and passive muscular protection of knee ligaments during external knee loading vs. size-matched men (125). This was most evident during torsional loading with increased knee internal rotation during jumping and pivoting maneuvers, which has been shown to increase ACL strain (125). Kiriyama et al. also found decreased tibial external rotation strength in female subjects, which correlated with increased internal rotation during single-leg drop landings (60). Increased knee internal rotation during impact-force absorption with decreased transverse plane control at the knee also occurs with increases in hamstring fatigue (3).

In addition to selective activation of medial vs. lateral hamstrings that may increase injury risk, numerous studies have elucidated a quadriceps dominance strategy in female athletes during sport tasks (48,80,83,84). Quadriceps dominance is an imbalance between the quadriceps and hamstring recruitment patterns (84). Female athletes demonstrating quadriceps dominance tend to preferentially increase their knee extensor moments over their knee flexor moments when performing sport movements with increased lower extremity demand (84). This quadriceps dominance strategy has been illustrated repeatedly in multiple studies of female athletes during sport tasks (16,95). Additionally, during testing by Huston and Wojtys designed to produce anterior tibial translation or shear, women demonstrated an over-reliance on quadriceps to stabilize the knee vs. male subjects. Quadriceps dominance tendencies may increase ACL injury risk (53). An implication of quadriceps dominance is decreased relative strength ratios of hamstrings to quadriceps. Hamstrings to quadriceps strength ratios of <0.55 have been identified as the benchmark for increased ACL injury risk (87). A prospective study by Myer et al. comparing female athletes with matched male and female controls found decreased hamstring strength in female injured ACL subjects but comparable quadriceps strength during isokinetic testing, reinforcing this quadriceps dominance pattern (80). Adolescent girls have been shown to exhibit less relative hamstring strength in comparison to age- and size-matched men, confirming the need for intervention in female athletes early in puberty (83,108).

In addition to relative hamstring weakness, women also needed increased time vs. men to reach maximum hamstring torque in a study by Huston and Wojtys (53). Women, unlike men, do not increase hamstrings to quadriceps torque ratios at velocities that approach those of functional activities (80). Unlike men, women demonstrated decreased hamstring-to-quadriceps ratios as knee flexion and extension angular velocity increased toward levels occurring in sports (80).

Fortunately, evidence demonstrates that hamstring activation is modifiable through neuromuscular intervention programs. In a separate study, Zebis et al. found that a neuromuscular training program based on a successful ACL injury prevention program format markedly increased prelanding and landing activation of the semitendinosis, which may assist in transverse plane and dynamic valgus control in athletes (130).

Hurd et al. found that perturbation training effects neuromuscular changes to decrease the quadriceps dominance pattern during a disturbed walking task, including earlier hamstring activation and higher hamstring EMG activity with lower peak and integrated vastus lateralis activity, and greater muscular cocontraction (52).

Holcomb et al. determined that 6 weeks of strength training was a sufficient duration to significantly increase the functional ratio of eccentric hamstring to concentric quadriceps torque to >1.0 (50). The method of strength training employed may also be an important factor in improving the hamstring-to-quadriceps ratio. Eccentric loading of the hamstrings was more effective in increasing hamstring-to-quadriceps strength ratios than traditional concentric exercises in multiple studies (57,78). Correcting low hamstring strength levels present in many female athletes during a warm-up format may be accomplished efficiently via partnered Russian hamstring curls (RHCs) (Figures 3A, B) and single-leg deadlifting with trunk rotation (Figures 4A, B) to emphasize eccentric hamstring loading and selective medial hamstring activation to control tibial rotation (27). The RHC has been identified as eliciting the highest percentage of MVIC in an EMG study comparing 6 hamstring exercises and also elicited the lowest MVIC percentage of quadriceps activation (27). Improvements in hamstring strength may allow female athletes to harness these strength gains via neuromuscular training to encourage increased knee flexed postures during athletic tasks allowing increased hamstring activation and subsequently decreased ACL strain (17). Movement speed and resistance may be altered to encourage strengthening and improve hamstring activation effects. Foot position may also be altered to facilitate activation of the medial hamstrings vs. lateral hamstrings

Figure 3. (A, B) Russian leg curl or Russian hamstring curl.

by internally rotating the foot during lower extremity exercises, specifically during single-leg deadlifting and hamstring bridging exercises (Figures 2A, B and 5), which can easily be performed on-field (69).

Leg Dominance

In addition to imbalance between quadriceps and hamstrings in some female athletes, Hewett et al. observed significant differences between legs, which they termed "leg dominance" (48). Differences in strength or power of 20% or more between limbs indicate a neuromuscular imbalance that may underlie significant injury risk (84).

This leg dominance may produce asymmetry during sport tasks. Significant side-to-side differences in knee valgus angle in adolescent girls have been observed during drop vertical jumps (36). The nondominant side had a larger peak vertical ground reaction force (VGRF) during the drop vertical jump, whereas the dominant side accepted larger forces during cutting maneuvers in female athletes suggesting varying asymmetry and differences depending on the sport movement. Brophy et al. supplied further evidence to support this leg dominance concept when they found significant side-to-side disparity in hip abductor strength in female soccer athletes that was not present in men (9). This emphasizes the need to incorporate neuromuscular training and plyometric exercises to focus on each leg in isolation and in tandem.

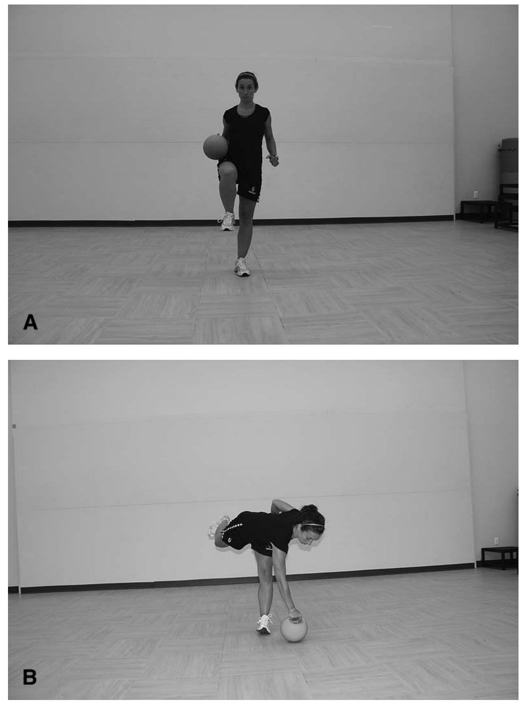

Figure 4. (A, B) Single-leg deadlift with trunk rotation (SLDLR) to selectively increase medial or lateral hamstring activity.

Core Training Component

Another factor implicated in female predisposition to noncontact ACL injury vs. men is weakness of core stabilizers. The biomechanical impact of core stability in relation to ACL injury risk may be recognized because increased lateral trunk flexion moves the ground reaction force vector laterally and increases the lever arm relative to the knee joint center, which

Figure 5. Bridging with foot rotated internally or externally to selectively increase medial or lateral hamstring activation respectively.

may increase the potential for knee valgus loading (47). A video study found that ACL-injured female subjects showed greater lateral trunk flexion and greater knee abduction or valgus motion at landing compared to injured male subjects and uninjured female control athletes (47). Ford et al. also demonstrated decreased active trunk control in both sagittal and frontal planes in women vs. men during single-leg landings (37). Decreased preactivation of the trunk and hip musculature may allow increased lateral trunk postures that may relate to increased knee valgus loads and postures. This increase in knee valgus alignment reduces the injury threshold of the knee (9,18). Zazulak et al. confirmed that factors related to core stability predicted ACL injury risk in athletes and that lateral angular displacement of the trunk would be the single best predictor or knee ligament injury in athletes (126). Increased lateral trunk displacement was consistently observed in ACL-injured athletes vs. uninjured athletes and decreased hip external rotation strength was the only predictor of combined back and lower extremity injury risk. Female athletes also demonstrated significantly decreased femoral abduction and external rotation strength and significantly decreased quadratus lumborum endurance compared with male athletes (126).

In addition to core weakness, Zazulak et al. also observed in a separate study that impaired core proprioception, measured by active proprioceptive repositioning of the trunk, could alter dynamic knee stability and predicted knee injury risk in female but not in male athletes (127). This relationship of core proprioception and ACL injury risk in women has also been documented by Hewett et al. who found that women with ACL-deficient knees and after ACL reconstruction possess greater deficits in proprioception and neuromuscular control, as measured by postural sway deficits, than their injured and reconstructed male counterparts (45).

Based on these data, it appears that programs incorporating core stability training including proprioceptive exercise, perturbations, and correction of body sway have the potential to limit noncontact ACL injury risk in female athletes (127). Too few studies have been performed to accurately evaluate the efficacy of training programs incorporating core stabilization exercises and effects on noncontact ACL injury rates. A recent pilot study by Myer et al. using a trunk neuromuscular training program increased standing hip abduction strength by 15% (79). Paterno et al. also concluded that core proprioceptive neuromuscular training improved body sway in the anterior–posterior but not medial–lateral plane in female athletes (99). This is significant because knee loading increases not only with frontal-plane deviations but may also be affected by variations in sagittal plane loading, particularly with variations in trunk posture. Blackburn and Padua found that higher ground reaction forces are associated with a more erect or upright landing posture during landings and that trunk flexion during landing reduced VGRFs and quadriceps activity (7). They theorized that this reduction in VGRF with increased trunk flexion occurred via increased knee and hip flexion angles during the landing task, which shifts the center of mass closer to knee joint. They noted that the significance of this change in trunk flexion angle was that lower ground reaction forces are likely associated with a lower quadriceps force requirement, potentially reducing the force imparted to the ACL (7). Changes in the amount of trunk flexion would likely impart varying demands on abdominal muscles for trunk flexion and erector spinae for trunk extension, and stabilizing muscles such as the transversus abdominus, multifidus, and rotators. Improving the efficiency of these muscles to stabilize the trunk in multiple planes appears to be beneficial in decreasing noncontact ACL injury risk in female athletes. Separate EMG studies indicate that prone trunk extension with upper and lower extremities lifted or "Superman" exercise (Figure 6) produced sufficient MVIC at the longissimus thoracis and lumbar multifidi for strengthening, whereas side-bridge or side plank MVIC was sufficient to strengthen external obliques (30,31). In addition, in an EMG study of abdominal muscle activation using commercially available equipment, Escamilla et al. found that the Power Wheel* roll-out was the most effective exercise in activating abdominal musculature while minimizing lumbar paraspinal and rectus femoris activity (32,33). This roll-out exercise (Figures 7A, B) may be simulated using soccer or basketballs, etc., and many of these core stabilization and strengthening exercises can be performed on-field without significant additional equipment. Overall, a limited number of well-designed studies exist in the literature comparing core stabilization exercises for athletic performance, making the development of a true evidence-based comprehensive core stability training program difficult.

*Jon. H Hinds, inventor of the Power Wheel and owner of Monkey Bar Gymnasium, 600 Williamson St, Suite K-2, Madison, WI 53703 (www.monkeybargym.com).

Feedforward Conditioning Mechanism

Research evidence estimates that ACL injuries occur in <100 milliseconds, whereas reflexive muscular activation takes an

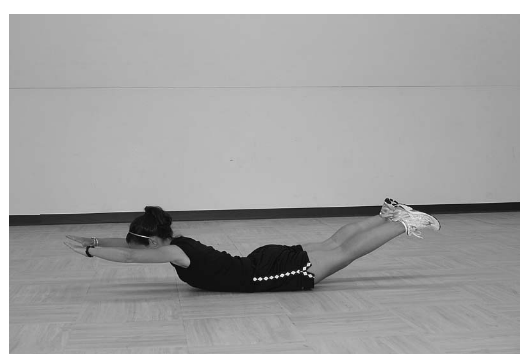

Figure 6. Superman, lumbar active extension can be advanced with use of weighted balls or partnered manual resistance.

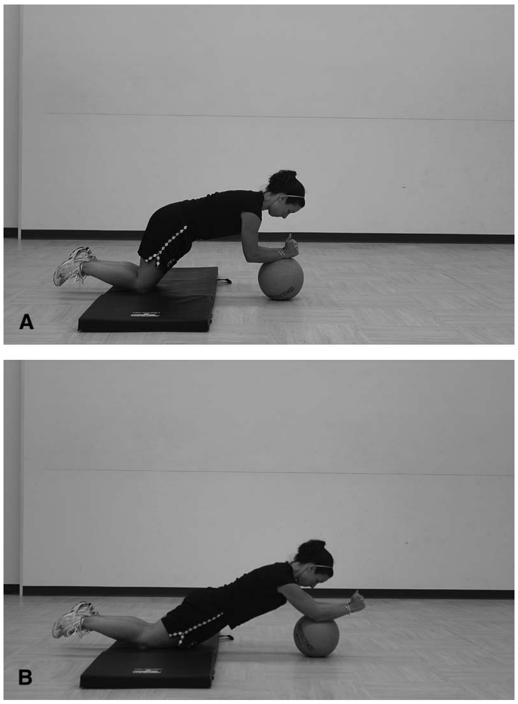

Figure 7. (A, B) Abdominal ball roll-out to simulate Power Wheel exercises

estimated 128 milliseconds (62). This suggests that ACL injuries occur too fast to allow a reflexive muscular response to prevent the injury (47,52). Chappell et al. showed that untrained female recreational athletes prepare for jump landings with decreased hip and knee flexion at landing, increased quadriceps and decreased hamstrings activation (16). This landing posture and muscle activation imbalance may increase ACL strain and suggests that untrained female athletes may demonstrate predisposition to noncontact ACL injury because of inherent preprogrammed motor strategies.

Based on this premise, 1 factor in the success of recent ACL injury prevention programs is likely attributed to an improvement in the efficiency of the feedforward mechanism for dynamic lower extremity stability. The feedforward mechanism may be defined as involuntary or automatic anticipatory postural adjustments or activation occurring before a perturbation (4). Female athletes may adopt preprogrammed or preparatory muscle recruitment and movement patterns that reduce the probability of injuries caused by unexpected perturbations that occur during sport tasks (45,47). This preparatory muscle activity may improve reactive muscle activity via the muscle spindle by identifying unexpected perturbations more quickly, and potentially reduce the risk for knee ligament injury (52). Increased excitation of afferent pathways to muscle spindles occurs with perturbations, suggesting reactivity may be improved with training (52). These preparatory or preprogrammed patterns may be modifiable and reinforced with specific neuromuscular training designed to simulate sport-specific tasks with an emphasis on safer kinematics. These modifications to existing motor patterns are particularly important because more organized and efficient muscular preactivation may increase knee joint stiffness and dynamic stability to protect articular structures (19).

Plyometrics

Plyometric training may induce these types of changes in muscle activation and feedforward programming via neuromuscular adaptations to the stretch reflex, elasticity of muscle, and Golgi tendon organs (19). Plyometric training has been shown to decrease peak ground reaction force, decrease hip abduction and adduction moments during landing, increase lower extremity muscle power, and decrease the incidence of serious knee injuries (44,46). Decreases in hip abduction and adduction moments may be enabled by increases in adductor and abductor coactivation to position the decelerating knee joint in a more neutral frontal-plane position (19). Lephart et al found similar changes in motor programming using plyometric training, including improvements in integrated and time to peak EMG activity of the gluteus medius before initial contact with the ground during landings after an 8-week training program (64). This suggests that subjects may position the thigh before ground contact in anticipation of the impact forces at landing that would cause hip adduction and knee valgus, possibly improving dynamic knee stability. The authors hypothesized that subjects might have maintained hip control by increasing the gluteus medius activation and timing to minimize joint displacement in the frontal, sagittal, and transverse planes (64).

Myer et al. found improvement in sagittal and frontal-plane kinematics after plyometric training, observing increased hip and knee flexion at landing (86). Improvements in movement kinematics have also been reported in other studies using multicomponent training designs with decreases in frontal-plane motion and increased knee flexion angles (17,42,87). Neuromuscular training emphasizing landing technique with increased knee flexion angles may also improve effectiveness of hamstrings activation to limit anterior tibial shear. Increased knee flexion and hip flexion during landing tensions the hamstring muscles to provide a posterior force upon the knee to protect the ACL. This contention is further supported by the increased peak hip and knee flexion moment during landing (64). Based on differences observed after incorporating plyometrics, training programs that incorporate safe levels of varus and valgus stress may induce more "muscle dominant" neuromuscular adaptations (87). Confirming this theory, Hewett et al. began a prospective study implementing 6 weeks of plyometric training in female soccer, basketball, and volleyball high school athletes in 1999 (44). Female athletes that did not receive the training program had a 3.6 times higher incidence of knee injury vs.

the trained group, suggesting significant benefits of plyometric neuromuscular training in female athletes (44). Hewett et al. completed a meta-analysis of ACL injury prevention programs that supplies more evidence for use of plyometrics. They found that 4 studies that used high-intensity plyometrics successfully reduced incidence of ACL injuries, while those that did not found no change in ACL injury incidence (43).

As noted previously, plyometric training should include isolated single-leg weight-bearing activities to minimize reinforcement of asymmetrical loading during double leg landings, decrease the potential influence of leg dominance on injury risk, and increase gluteal muscle activation. Plyometric training should occur in multiple movement planes to mimic sport demands and encourage diverse muscle activation and training. Cowley et al. reinforced this sport-specific training principle in their study, which found significant neuromuscular and biomechanical differences, and differences in ACL injury frequency, between female soccer and basketball athletes during cutting vs. jumping and landing tasks respectively (20).

Plyometric Technique and Monitoring

Technique during plyometrics and sport-specific tasks should be closely monitored by strength and conditioning professionals. Mizner et al. found that trunk and lower extremity strength were poor predictors of improvements in landing mechanics but that female athletes were able to make significant positive changes in landing mechanics in repeat trials after brief verbal instruction (77). Similarly, Padua et al. completed a systematic review of 6 studies assessing ACL injury prevention programs and found that each study demonstrating significant decreases in VGRF used verbal instructions and feedback for proper landing technique, auditory cues for minimizing landing forces, and performance under direct supervision on a regular basis (96). In contrast, those studies indicating no change in VGRF did not incorporate regular verbal or auditory feedback and performance under direct supervision on a regular basis (96). Prapavessis and McNair successfully demonstrated that subjects were capable of decreasing ground reaction force with jumping via altered technique after only 1 feedback session (106). Female athletes can also be trained to alter their knee range of motion (ROM) beneficially during landing when verbally cued (22,93,106,107). The emphasis on ROM, specifically increased hip and knee flexion during landing is particularly important because women landing in less knee and hip flexion demonstrate increased knee valgus angles, decreased energy absorption, and increased vastus lateral activity (96). These biomechanical changes potentially increase ACL injury risk as noted previously.

Balance

Several studies have also noted a significant reduction in ACL injury risk factors using balance and proprioceptive training in isolation and as part of a multicomponent program (15,51,99). Paterno et al. did confirm increases in single-leg total dynamic stability and in anterior–posterior balance with a 6-week neuromuscular training program for ACL injury prevention (99). Fitzgerald et al. also demonstrated improvements in function, crossover hop test scores, and knee stability using perturbation training in ACL-injured subjects, suggesting beneficial alteration of motor patterns (34). Hurd et al. found perturbation and balance training improved relative quadriceps to hamstring ratio on integrated EMG with improved hamstring and gastrocnemius activation timing after training, potentially decreasing ACL strain (52). Padua et al. also noted improvements in biomechanics and muscular stability with perturbation training, stating that perturbation training and exercises that require balancing on a single leg have increased antagonist coactivation of the knee flexor muscles, which may produce greater knee flexion (94). Although many of these studies used additional equipment including unstable surfaces, on-field challenges to balance may be performed in single-leg stance using partnered manual perturbations, eyes closed to decrease visual feedback, and sport-specific dynamic balance challenges, which have all been found to improve dynamic balance in healthy individuals (Figures 8A–C) (26). Additionally, gastrocnemius and soleus training may also be an important element in enhancing balance and limiting injury risk. Fatigue at the ankle plantar flexors was found to impair single-leg stance postural control and overall stability (110). The gastrocnemius and ankle musculature may also act as a synergistic and compensatory dynamic knee stabilizer in female athletes in closed kinetic chain situations as the quadriceps fatigue (90,94). Gastrocnemius training to improve strength and endurance may be easily accomplished on-field using single-leg calf raises with manual partnered, weighted, or elastic band resistance.

Agility Training

Cutting and change of direction maneuvers occur repeatedly during sport and have been identified as a frequent cause of ACL injury in female athletes (44). Imwalle et al. found significant increases in internal rotation at the hip and knee during a 90° cutting maneuver vs. 45° (54). In addition, Ebben found women sustain quadriceps activation longer during cutting and had lower hamstring-to-quadriceps activation ratios (28). This reinforces a need for neuromuscular movement training at various angles and planes, and hip, hamstring, and core strengthening to limit increased vulnerability to ACL injury during these movements. Agility training with an emphasis on safe mechanics and posture is imperative, particularly the inclusion of unanticipated change of direction, which may more closely simulate sport conditions. Unanticipated sidestep cutting was shown to increase varus-valgus and internal–external knee moments (113). Unanticipated sidestep cutting has been demonstrated to increase muscle activation before initial contact, suggesting the importance of feedforward motor planning discussed earlier. These motor planning strategies may be modifiable

Figure 8. (A–C) Perturbations in single-leg stance position including sport-specific adaptations. Amount, location, direction, and speed of manual perturbation force can be varied to advance exercise difficulty. Eyes can also be closed to increase balance challenge.

through supervised neuromuscular training that induces safe levels of knee instability to facilitate neuromuscular adaptation (5,6). Anterior cruciate ligament injury risk in women is increased during lateral reactive jumps based on decreased knee flexion and increased valgus angles known to increase ACL strain and frequently observed during noncontact ACL injury (113). Lateral jumps in women produced higher GRF, anterior tibial shear, and valgus and flexion moments (113). These forces were further increased when subjects performed the movements in a reactive manner vs. planned. Brown et al. also found significant differences in hip and knee postures in unanticipated vs. anticipated landings and felt that unanticipated training may be useful to promote central control adaptations during sport tasks (14). These research studies underscore the need for unanticipated reactive change of direction movements, particularly laterally, as a component in ACL injury prevention training for female athletes. A 6-week agility training program incorporating unanticipated directional changes demonstrated improved medial hamstring activation during pivoting and decreased vastus medialis oblique activation during ground contact (122). A 6-week training program involving modification of cutting technique via verbal and visual feedback also resulted in statistically significant reductions in knee valgus loading during sidestep cutting in planned and unplanned conditions (24). This reinforces the ability of supervised agility training to promote changes in both neuromuscular activation and biomechanical postural changes to potentially decrease ACL injury risk.

Stretching

Pollard et al. found that ankle dorsiflexion ROM was negatively correlated with frontal-plane knee excursion and suggested that a restriction in the forward progression of the tibia during deceleration may produce compensatory hip internal rotation or foot pronation to control the body's center of mass (106). This makes gastrocnemius and soleus static stretching to improve flexibility an essential part of ACL injury prevention programs to allow improved dorsiflexion ROM (130). Maintaining adequate flexibility of the quadriceps and hamstrings is also critical to allow sufficient knee flexion and hip flexion, respectively, during sport maneuvers to limit ACL strain in these positions as noted previously. However, although static stretching warm-up may improve flexibility, dynamic warm-ups have demonstrated improved effects on power and agility test scores vs. static stretching warm-ups (66,75). Dynamic warm-up activities should be incorporated as the first phase of the warm-up program.

Program Duration

Myer et al. determined that a 7-week neuromuscular training program was effective in decreasing predetermined risk factors for ACL injury; however, it was not effective enough to reduce levels for female athletes categorized as high risk to those of athletes categorized as low risk after training (82). They determined that "increased training volume or more specific techniques may be necessary for high-risk [female] athletes to substantially decrease ACL injury risk." Brophy et al. also reiterated the minimum of 6–8 weeks to effect neuromuscular changes based on the significant decrease in noncontact ACL injury rate in the intervention group of the Prevent Injury and Enhance Performance program by Mandelbaum et al. after 6 weeks vs. controls (13,70). Based on those results, it is believed that programs should be 8 or more weeks in duration to allow sufficient neuromuscular changes and performance training effects, especially in female athletes demonstrating risk factors noted previously that may increase their susceptibility to noncontact ACL injury. However, limited research evidence exists regarding optimal training duration and volume to obtain the most effective results.

Screening

Although these warm-up programs may be universally implemented with female athletes, a formal prescreening program may help in identifying female athletes possessing some of the risk factors identified in this article, and potentially most at risk for ACL injury. Hand-held dynamometry is reliable in young, active women and may be effectively used to identify female athletes with weakness of the gluteus medius and maximus in hip abduction and extension or external rotation, respectively, suspected to increase injury susceptibility (58). Additionally, hamstring weakness may be identified using hand-held dynamometry and compared to quad strength, although hamstring-to-quadriceps activation ratios and timing of activation may be more essential in determining ACL injury risk than static strength measures. However, these measures are not easily obtainable without more expensive testing equipment that requires increased time demands, training, and skill.

Hip and knee pathomechanics in the frontal plane during athletic tasks, specifically “valgus collapse” or “dynamic knee valgus” have been found to be reliably identified using video analysis and visual observation (29,74). Videoed drop jump tasks have been proved to be reliable means to predict ACL injury risk in women and detect some of these pathomechanical postures, including excessive hip adduction, femoral internal rotation, tibial external rotation, and foot pronation postures (45). Another advantage of the videoed drop jump task is that video feedback of landing technique in conjunction with verbal feedback to participants has a compounding beneficial effect on landing technique and reduction in VGRF that is retained (92). Myer et al. have progressed the drop jump analysis to a tuck jump assessment involving a series of successive jumps over a 10-second period. This tool has a defined checklist of biomechanical and technique flaws that may assist the clinician in identifying injury risk and plyometric technique; however, validity and reliability of the tuck jump assessment have not been formally established (85).

Similarly, Padua et al. have developed the Landing Error Scoring System (LESS) as a clinical tool with confirmed validity and reliability to assess jump landing biomechanics that may assist in identifying female athletes with higher risk of ACL injury (97). However, one drawback the authors acknowledge is that the LESS’s dependence on the use of a drop jump assessment may be insufficient to detect injury risk in athletes during a side or crosscutting maneuver, common in many sports such as soccer, lacrosse, etc. Similar limitations exist with screening using exclusively drop landings or jumps.

These limitations suggest a possible role for the use of multiple forms of testing in a variety of planes and movements to assess ACL injury risk. Lower extremity functional testing may be incorporated as a screening tool to assess neuromuscular control in horizontal tasks vs. vertically-oriented drop landing or jump tasks. Four lower extremity functional tests have been found reliable, including the following: single-leg hop for distance, triple hop for distance, 6-m timed hop, and crossover hop test (10,111). These tests may be useful to visually identify neuromuscular pathomechanics during these single-leg tasks that replicate sport-specific movements and predispose female athletes to ACL injury risk. These tests are also essential to identify asymmetry between legs or leg dominance as discussed previously, with differences of 20% or more considered to increase injury risk (84). Recently, Hickey et al. also demonstrated good reliability in the use of a modified agility *T*-test, incorporating 2 90° single-leg cuts to identify lower extremity asymmetry, and subsequently potential injury risk (49). The modified agility *T*-test may also allow visual examination of pathomechanics during cutting maneuvers that may not have presented during drop landing or jump tasks. The Star Excursion Balance Test has also been found to be a reliable tool to assess dynamic lower extremity balance and stability, and predicting lower extremity injury risk (59,102).

Universally and accurately defining and assessing core stability has proved elusive, and a scarcity of valid and reliable core stability assessment measures exist in the literature. Debate continues over which muscles comprise the core, whether endurance or strength is more critical to core stability and athletic performance, and the best means to assess these factors. Cowley et al. successfully demonstrated reliable assessment of core musculature power using front and side medicine ball tosses (21). A single-leg squat test has also been advocated not only to identify hip and knee pathomechanics as noted previously, but also as a screening for core stability (55,63,123). However, Weir et al. showed insufficient reliability of 6 clinical tests commonly used to assess core stability including the following: unilateral squat, lateral step-downs, bridging or prone plank, and observation of standing dynamic trunk control in the frontal, sagittal, and transverse planes (121). More research is needed to develop valid and reliable core stability assessment tools that can be confidently included as part of a more comprehensive screening process for ACL injury risk in women.

A combination of these tools may be useful to successfully identify neuromuscular factors shown to increase noncontact ACL injury risk in women during a screening process. These screening tools can all be practically applied in an on-field setting with minimal equipment needs and have well-researched validity and reliability. This screening process may allow customized development of a corrective exercise program to address individual deficits and decrease injury risk. A prescreening using these measures will also allow the strength and conditioning professional to establish objective baseline measures for each participant to track progress and changes to assess training effects.

Summary

The surge in recent research and development of ACL injury prevention warm-up programs has produced a diversity of program offerings, making it essential to be able to identify biomechanical and neuromuscular risk factors in female athletes and develop programs to address specific deficits. Program supervisors must have a thorough understanding of the susceptibility at each region in the entire kinetic chain from the trunk to the foot. The influence of neuromuscular control and biomechanical faults at the trunk and lower extremities appear repeatedly throughout video analyses of ACL injury mechanisms and clinical research studies, and appear distinctly different in women vs. men. Based on available research evidence, it appears that multicomponent neuromuscular training programs consisting of training for the hip and hamstrings, core stabilization, plyometrics and neuromuscular training, balance and proprioception, agility training, and stretching are critical to limiting this ACL injury risk in women. This training may be introduced in warm-up format with essential verbal and visual feedback provided to participants. Programs producing measurable performance gains in athletic ability may foster improved adherence to training. Programs should be 8 or more weeks in duration to allow sufficient time for neuromuscular changes based on available literature. Further research studies to refine and critically examine the most critical elements and ideal training frequency and volume are essential to the continued future success of ACL injury prevention programs in female athletes. A multicomponent prescreening process incorporating various athletic movements in multiple planes may also prove useful to successfully identify female athletes with the greatest amount of pathology suspected to contribute to noncontact ACL injury risk and to establish baseline values to measure participant progress and training effects.

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References

1. Agel, J, Arendt, EA, and Bershadsky, B. Anterior cruciate ligament injury in national collegiate athletic association basketball and soccer: A 13-year review. *Am J Sports Med* 33: 524–530, 2005.
2. Alentorn-Geli, E, Myer, GD, Silvers, HJ, Samitier, G, Romero, D, Lázaro-Haro, C, and Cugat, R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors. *Knee Surg Sports Traumatol Arthrosc* 17: 705–729, 2009.
3. Alentorn-Geli, E, Myer, GD, Silvers, HJ, Samitier, G, Romero, D, Lazaro-Haro, C, and Cugat, R. Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 2: A review of prevention programs aimed to modify risk factors and to reduce injury rates. *Knee Surg Sport Traumatol Arthrosc* 17: 859–879, 2009.
4. Allison, GT, Morris, SL, and Lay, B. Feedforward responses of transversus abdominis are directionally specific and act asymmetrically: Implications for core stability theories. *J Orthop Sports Phys Ther* 38: 228–237, 2008.
5. Besier, TF, Lloyd, DG, and Ackland, TR. Muscle activation strategies at the knee during running and cutting maneuvers. *Med Sci Sports Exerc* 35: 119–127, 2003.
6. Besier, TF, Lloyd, DG, Ackland, TR, and Cochrane, JL. Anticipatory effects on knee joint loading during running and cutting maneuvers. *Med Sci Sports Exerc* 33: 1176–1181, 2001.
7. Blackburn, JT and Padua, DA. Sagittal-plane trunk position, landing forces, and quadriceps electromyographic activity. *J Athl Train* 44: 174–179, 2009.
8. Boden, BP, Dean, GS, Feagin JA Jr, and Garrett, WE Jr. Mechanisms of anterior cruciate ligament injury. *Orthopedics* 23: 573–578, 2000.
9. Boden, BP, Torg, JS, Knowles, SB, and Hewett, TE. Video analysis of anterior cruciate ligament injury: Abnormalities in hip and ankle kinematics. *Am J Sports Med* 37: 252–259, 2009.
10. Bolgla, LA and Keskula, DR. Reliability of lower extremity functional performance tests. *J Orthop Sports Phys Ther* 26: 138–142, 1997.
11. Borotikar, BS, Newcomer, R, Koppes, R, and McLean, SG. Combined effects of fatigue and decision making on female lower limb landing postures: Central and peripheral contributions to ACL injury risk. *Clin Biomech (Bristol, Avon)* 23: 81–92, 2008.
12. Brophy, RH, Chiaia, TA, Maschi, R, Dodson, CC, Oh, LS, Lyman, S, Allen, AA, and Williams, RJ. The core and hip in soccer athletes compared by gender. *Int J Sports Med* 30: 663–667, 2009.
13. Brophy, RH, Silvers, HJ, and Mandelbaum, BR. Anterior cruciate ligament injuries: Etiology and prevention. *Sports Med Arthrosc* 18: 2–11, 2010.
14. Brown, TN, Palmieri-Smith, RM, and McLean, SG. Differences between sexes and limbs in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: Implications for ACL injury. *Br J Sports Med* 2009 April 16. [Epub ahead of print]
15. Caraffa, A, Cerulli, G, Projetti, M, Aisa, G, and Rizzo, A. Prevention of anterior cruciate ligament injuries in soccer. A prospective controlled study of proprioceptive training. *Knee Surg Sports Traumatol Arthrosc* 4: 19–21, 1996.
16. Chappell, JD, Creighton, RA, Giuliani, C, Yu, B, and Garrett, WE. Kinematics and electromyography of landing preparation in vertical stop-jump: Risks for noncontact anterior cruciate ligament injury. *Am J Sports Med* 35: 235–241, 2007.
17. Chappell, JD and Limpisvasti, O. Effect of a neuromuscular training program on the kinetics and kinematics of jumping tasks. *Am J Sports Med* 36: 1081–1086, 2008.
18. Chaudhari, AM and Andriacchi, TP. The mechanical consequences of dynamic frontal plane limb alignment for non-contact ACL injury. *J Biomech* 39: 330–338, 2006.
19. Chimera, NJ, Swanik, KA, Swanik, CB, and Straub, SJ. Effects of plyometric training on muscle-activation strategies and performance in female athletes. *J Athl Train* 39: 24–31, 2004.
20. Cowley, HR, Ford, KR, Myer, GD, Kernozek, TW, and Hewett, TE. Differences in neuromuscular strategies between landing and cutting tasks in female basketball and soccer athletes. *J Athl Train* 41: 67–73, 2006.
21. Cowley, PM and Swensen, TC. Development and reliability of two core stability field tests. *J Strength Cond Res* 22: 619–624, 2008.

22. Cowling, EJ, Steele, JR, and McNair, PJ. Effect of verbal instructions on muscle activity and risk of injury to the anterior cruciate ligament during landing. *Br J Sports Med* 37: 126–130, 2003.

23. DeMont, RG and Lephart, SM. Effect of sex on preactivation of the gastrocnemius and hamstring muscles. *Br J Sports Med* 38: 120–124, 2004.

24. Dempsey, AR, Lloyd, DG, Elliott, BC, Steele, JR, and Munro, BJ. Changing sidestep cutting technique reduces knee valgus loading. *Am J Sports Med* 37: 2194–2200, 2009.

25. Distefano, LJ, Blackburn, JT, Marshall, SW, and Padua, DA. Gluteal muscle activation during common therapeutic exercises. *J Orthop Sports Phys Ther* 39: 532–540, 2009.

26. DiStefano, LJ, Clark, MA, and Padua, DA. Evidence supporting balance training in healthy individuals: A systemic review. *J Strength Cond Res* 23: 2718–2731, 2009.

27. Ebben, WP. Hamstring activation during lower body resistance training exercises. *Int J Sports Physiol Perform* 4: 84–96, 2009.

28. Ebben, WP, Fauth, ML, Petushek, EJ, Garceau, LR, Hsu, BE, Lutsch, BN, and Feldmann, CR. Gender-based analysis of hamstring and quadriceps muscle activation during jump landings and cutting. *J Strength Cond Res* 24: 408–415, 2010.

29. Ekegren, CL, Miller, WC, Celebrini, RG, Eng, JJ, and Macintyre, DL. Reliability and validity of observational risk screening in evaluating dynamic knee valgus. *J Orthop Sports Phys Ther* 39: 665–674, 2009.

30. Ekstrom, RA, Donatelli, RA, and Carp, KC. Electromyographic analysis of core trunk, hip, and thigh muscles during 9 rehabilitation exercises. *J Orthop Sports Phys Ther* 37: 754–762, 2007.

31. Ekstrom, RA, Osborn, RW, and Hauer, PL. Surface electromyographic analysis of the low back muscles during rehabilitation exercises. *J Orthop Sports Phys Ther* 38: 736–745, 2008.

32. Escamilla, RF, Babb, E, DeWitt, R, Jew, P, Kelleher, P, Burnham, T, Busch, J, D'Anna, K, Mowbray, R, and Imamura, RT. Electromyographic analysis of traditional and nontraditional abdominal exercises: Implications for rehabilitation and training. *Phys Ther* 86: 656–671, 2006.

33. Escamilla, RF, McTaggart, MS, Fricklas, EJ, DeWitt, R, Kelleher, P, Taylor, MK, Hreljac, A, and Moorman, CT. An electromyographic analysis of commercial and common abdominal exercises: Implications for rehabilitation and training. *J Orthop Sports Phys Ther* 36: 45–57, 2006.

34. Fitzgerald, GK, Axe, MJ, and Snyder-Mackler, L. The efficacy of perturbation training in nonoperative anterior cruciate ligament rehabilitation programs for physical active individuals. *Phys Ther* 80: 128–140, 2000.

35. Fleming, BC. Biomechanics of the anterior cruciate ligament. *J Orthop Sports Phys Ther* 33: A13–A15, 2003.

36. Ford, KR, Myer, GD, and Hewett, TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc* 35: 1745–1750, 2003.

37. Ford, KR, Myer, GD, and Hewett, TE. Increased trunk motion in female athletes compared to males during single leg landing. *Med Sci Sports Exerc* 39: S70, 2007.

38. Ford, KR, Myer, GD, Toms, HE, and Hewett, TE. Gender differences in the kinematics of unanticipated cutting in young athletes. *Med Sci Sports Exerc* 37: 124–129, 2005.

39. Gilchrist, J, Mandelbaum, BR, Melancon, H, Ryan, GW, Silvers, HJ, Griffin, LY, Watanabe, DS, Dick, RW, and Dvorak, J. A randomized controlled trial to prevent noncontact anterior cruciate ligament injury in female collegiate soccer players. *Am J Sports Med* 36: 1476–1483, 2008.

40. Hägglund, M, Waldén, M, and Atroshi, I. Preventing knee injuries in adolescent female football players–design of a cluster randomized controlled trial [NCT00894595]. *BMC Musculoskelet Disord* 23; 10: 75, 2009.

41. Herman, DC, Oñate, JA, Weinhold, PS, Guskiewicz, KM, Garrett, WE, Yu, B, and Padua, DA. The effects of feedback with and without strength training on lower extremity biomechanics. *Am J Sports Med* 37: 1301–1308, 2009.

42. Herman, DC, Weinhold, PS, Guskiewicz, KM, Garrett, WE, Yu, B, and Padua, DA. The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task. *Am J Sports Med* 36: 733–740, 2008.

43. Hewett, TE, Ford, KR, and Myer, GD. Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *Am J Sports Med* Mar; 34: 490–498, 2006.

44. Hewett, TE, Lindenfeld, TN, Riccobene, JV, and Noyes, FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. A prospective study. *Am J Sports Med* 27: 699–706, 1999.

45. Hewett, TE, Myer, GD, Ford, KR, Heidt, RS Jr, Colosimo, AJ, McLean, SG, van den Bogert, AJ, Paterno, MV, and Succop, P. 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* 33: 492–501, 2005.

46. Hewett, TE, Stroupe, AL, Nance, TA, and Noyes, FR. Plyometric training in female athletes. Decreased impact forces and increased hamstring torques. *Am J Sports Med* 24: 765–773, 1996.

47. Hewett, TE, Torg, JS, and Boden, BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: Lateral trunk and knee abduction moments are combined components of the injury mechanism. *Br J Sports Med* 43: 417–422, 2009.

48. Hewett, TE, Zazulak, BT, Myer, GD, and Ford, KR. A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes. *Br J Sports Med* 39: 347–350, 2005.

49. Hickey, KC, Quatman, CE, Myer, GD, Ford, KR, Brosky, JA, and Hewett, TE. Methodological report: Dynamic field tests used in an NFL combine setting to identify lower-extremity functional asymmetries. *J Strength Cond Res* 23: 2500–2506, 2009.

50. Holcomb, WR, Rubley, MD, Lee, HJ, and Guadagnoli, MA. Effect of hamstring-emphasized resistance training on hamstring:quadriceps strength ratios. *J Strength Cond Res* 21: 41–47, 2007.

51. Holm, I, Fosdahl, MA, Friis, A, Risberg, MA, Myklebust, G, and Steen, H. Effect of neuromuscular training on proprioception, balance, muscle strength, and lower limb function in female team handball players. *Clin J Sport Med* 14: 88–94, 2004.

52. Hurd, WJ, Chmielewski, TL, and Snyder-Mackler, L. Perturbation-enhanced neuromuscular training alters muscle activity in female athletes. *Knee Surg Sports Traumatol Arthrosc* 14: 60–69, 2006.

53. Huston, LJ and Wojtys, EM. Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med* 24: 427–436, 1996.

54. Imwalle, LE, Myer, GD, Ford, KR, and Hewett, TE. Relationship between hip and knee kinematics in athletic women during cutting maneuvers: A possible link to noncontact anterior cruciate ligament injury and prevention. *J Strength Cond Res.* 23: 2223–2230, 2009.

55. Ireland, ML. The female ACL: Why is it more prone to injury? *Orthop Clin North Am* 33: 637–651, 2002.

56. Jacobs, CA, Uhl, TL, Mattacola, CG, Shapiro, R, and Rayens, WS. Hip abductor function and lower extremity landing kinematics: Sex differences. *J Athl Train* 42: 76–83, 2007.

57. Kaminski, TW, Wabbersen, CV, and Murphy, RM. Concentric versus enhanced eccentric hamstring strength training: Clinical implications. *J Athl Train* 33: 216–221, 1998.

58. Kelln, BM, McKeon, PO, Gontkof, LM, and Hertel, J. Hand-held dynamometry: Reliability of lower extremity muscle testing in

healthy, physically active, young adults. *J Sport Rehabil* 17: 160–170, 2008.

59. Kinzey, SJ and Armstrong, CW. The reliability of the star-excursion test in assessing dynamic balance. *J Orthop Sports Phys Ther* 27: 356–360, 1998.
60. Kiriyama, S, Sato, H, and Takahira, N. Gender differences in rotation of the shank during single-legged drop landing and its relation to rotational muscle strength of the knee. *Am J Sports Med* 37: 168–174, 2009.
61. Krause, DA, Jacobs, RS, Pilger, KE, Sather, BR, Sibunka, SP, and Hollman, JH. Electromyographic analysis of the gluteus medius in five weight-bearing exercises. *J Strength Cond Res* 23: 2689–2694, 2009.
62. Krosshaug, T, Nakamae, A, Boden, BP, Engebretsen, L, Smith, G, Slauterbeck, JR, Hewett, TE, and Bahr, R. Mechanisms of anterior cruciate ligament injury in basketball: Video analysis of 39 cases. *Am J Sports Med* 35: 359–367, 2007.
63. Leetun, DT, Ireland, ML, Willson, JD, Ballantyne, BT, and Davis, IM. Core stability measures as risk factors for lower extremity injury in athletes. *Med Sci Sports Exerc* 36: 926–934, 2004.
64. Lephart, SM, Abt, JP, Ferris, CM, Sell, TC, Nagai, T, Myers, JB, and Irrgang, JJ. Neuromuscular and biomechanical characteristic changes in high school athletes: A plyometric versus basic resistance program. *Br J Sports Med* 39: 932–938, 2005.
65. Lim, BO, Lee, YS, Kim, JG, An, KO, Yoo, J, and Kwon, YH. Effects of sports injury prevention training on the biomechanical risk factors of anterior cruciate ligament injury in high school female basketball players. *Am J Sports Med* 37: 1728–1734, 2009.
66. Little, T and Williams, AG. Effects of differential stretching protocols during warm-ups on high-speed motor capacities in professional soccer players. *J Strength Cond Res* 20: 203–207, 2006.
67. Lloyd, DG and Buchanan, TS. Strategies of muscular support of varus and valgus isometric loads at the human knee. *J Biomech* 34: 1257–1267, 2001.
68. Lohmander, LS, Englund, PM, Dahl, LL, and Roos, EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: Osteoarthritis. *Am J Sports Med* 35: 1756–1769, 2007.
69. Lynn, SK and Costigan, PA. Changes in the medial-lateral hamstring activation ratio with foot rotation during lower limb exercise. *J Electromyogr Kinesiol* 19: e197–e205, 2009.
70. Mandelbaum, BR, Silvers, HJ, Watanabe, DS, Knarr, JF, Thomas, SD, Griffin, LY, Kirkendall, DT, and Garrett, W Jr. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *Am J Sports Med* 33: 1003–1010, 2005.
71. Markolf KL, Graff-Radford A, Amstutz HC. In vivo knee stability. A quantitative assessment using an instrumented clinical testing apparatus. *J Bone Joint Surg Am* 60(5): 664–674, 1978.
72. Mascal, CL, Landel, R, and Powers, C. Management of patellofemoral pain targeting hip, pelvis, and trunk muscle function: 2 case reports. *J Orthop Sports Phys Ther* 33: 647–660, 2003.
73. McLean, SG, Borotikar, B, and Lucey, SM. Lower limb muscle pre-motor time measures during a choice reaction task associate with knee abduction loads during dynamic single leg landings. *Clin Biomech (Bristol, Avon)* 25: 563–569, 2010.
74. McLean, SG, Walker, K, Ford, KR, Myer, GD, Hewett, TE, and van den Bogert, AJ. Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *Br J Sports Med* 39: 355–362, 2005.
75. McMillian, DJ, Moore, JH, Hatler, BS, and Taylor, DC. Dynamic vs. static-stretching warm up: The effect on power and agility performance. *J Strength Cond Res* 20: 492–499, 2006.
76. McNair, PJ, Marshall, RN, and Matheson, JA. Important features associated with acute anterior cruciate ligament injury. *N Z Med J* 103: 537–539, 1990.
77. Mizner, RL, Kawaguchi, JK, and Chmielewski, TL. Muscle strength in the lower extremity does not predict postinstruction improvements in the landing patterns of female athletes. *J Orthop Sports Phys Ther* 38: 353–361, 2008.
78. Mjølsnes, R, Arnason, A, Østhagen, T, Raastad, T, and Bahr, R.A 10-week randomized trial comparing eccentric vs. concentric hamstring strength training in well-trained soccer players. *Scand J Med Sci Sports* 14: 311–317, 2004.
79. Myer, GD, Chu, DA, Brent, JL, and Hewett, TE. Trunk and hip control neuromuscular training for the prevention of knee joint injury. *Clin Sports Med* 27: 425–448, 2008.
80. Myer, GD, Ford, KR, Barber Foss, KD, Liu, C, Nick, TG, and Hewett, TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med* 19: 3–8, 2009.
81. Myer, GD, Ford, KR, Brent, JL, and Hewett, TE. The effects of plyometric vs. dynamic stabilization and balance training on power, balance, and landing force in female athletes. *J Strength Cond Res* 20: 345–353, 2006.
82. Myer, GD, Ford, KR, Brent, JL, and Hewett, TE. Differential neuromuscular training effects on ACL injury risk factors in "high risk" versus "low risk" athletes. *BMC Musculoskelet Disord* 8: 39, 2007.
83. Myer, GD, Ford, KR, Divine, JG, Wall, EJ, Kahanov, L, and Hewett, TE. Longitudinal assessment of noncontact anterior cruciate ligament injury risk factors during maturation in a female athlete: A case report. *J Athl Train* 44: 101–109, 2009.
84. Myer, GD, Ford, KR, and Hewett, TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *J Athl Train* 39: 352–364, 2004.
85. Myer, GD, Ford, KR, and Hewett, TE. Tuck jump assessment for reducing anterior cruciate ligament injury risk. *Athl Ther Today* 13: 39–44, 2008.
86. Myer, GD, Ford, KR, McLean, SG, and Hewett, TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *Am J Sports Med* 34: 445–455, 2006.
87. Myer, GD, Ford, KR, Palumbo, JP, and Hewett, TE. Neuromuscular training improves performance and lower-extremity biomechanics in female athletes. *J Strength Cond Res* 19: 51–60, 2005.
88. Myklebust, G, Engebretsen, L, Braekken, IH, Skjølberg, A, Olsen, OE, and Bahr, R. Prevention of anterior cruciate ligament injuries in female team handball players: A prospective intervention study over three seasons. *Clin J Sport Med* 13: 71–78, 2003.
89. Neumann, DA. *Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation*. St. Louis, MO: Mosby, 2002.
90. Nyland, JA, Caborn, DN, Shapiro, R, and Johnson, DL. Fatigue after eccentric quadriceps femoris work produces earlier gastrocnemius and delayed quadriceps femoris activation during crossover cutting among normal athletic women. *Knee Surg Sports Traumatol Arthrosc* 5: 162–167, 1997.
91. Olsen, OE, Myklebust, G, Engebretsen, L, and Bahr, R. Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. *Am J Sports Med* 32: 1002–1012, 2004.
92. Oñate, JA, Guskiewicz, KM, Marshall, SW, Giuliani, C, Yu, B, and Garrett, WE. Instruction of jump-landing technique using videotape feedback: Altering lower extremity motion patterns. *Am J Sports Med* 33: 831–842, 2005.
93. Onate, JA, Guskiewicz, KM, and Sullivan, RJ. Augmented feedback reduces jump landing forces. *J Orthop Sports Phys Ther* 31: 511–517, 2001.
94. Padua, DA, Arnold, BL, Perrin, DH, Gansneder, BM, Carcia, CR, and Granata, KP. Fatigue, vertical leg stiffness, and stiffness control strategies in males and females. *J Athl Train* 41: 294–304, 2006.
95. Padua, DA, Carcia, CR, Arnold, BL, and Granata, KP. Gender differences in leg stiffness and stiffness recruitment strategy during two-legged hopping. *J Mot Behav* 37: 111–125, 2005.

96. Padua, DA and DiStefano, LJ. Sagittal plane knee biomechanics and vertical ground reaction forces are modified following ACL injury prevention programs: A systematic review. *Sports Health* 1: 165–173, 2009.

97. Padua, DA, Marshall, SW, Boling, MC, Thigpen, CA, Garrett, WE Jr, and Beutler AI. The Landing Error Scoring System (LESS) is a valid and reliable clinical assessment tool of jump-landing biomechanics: The JUMP-ACL study. *Am J Sports Med* 37: 1996–2002, 2009.

98. Palmieri-Smith, RM, McLean, SG, Ashton-Miller, JA, and Wojtys, EM. Association of quadriceps and hamstrings cocontraction patterns with knee joint loading. *J Athl Train* 44: 256–263, 2009.

99. Paterno, MV, Myer, GD, Ford, KR, and Hewett, TE. Neuromuscular training improves single-limb stability in young female athletes. *J Orthop Sports Phys Ther* 34: 305–316, 2004.

100. Petersen, W, Braun, C, Bock, W, Schmidt, K, Weimann, A, Drescher, W, Eiling, E, Stange, R, Fuchs, T, Hedderich, J, and Zantop, T. A controlled prospective case control study of a prevention training program in female team handball players: The German experience. *Arch Orthop Trauma Surg* 125: 614–621, 2005.

101. Pfeiffer, RP, Shea, KG, Roberts, D, Grandstrand, S, and Bond, L. Lack of effect of a knee ligament injury prevention program on the incidence of noncontact anterior cruciate ligament injury. *J Bone Joint Surg Am* 88: 1769–1774, 2006.

102. Plisky, PJ, Rauh, MJ, Kaminski, TW, and Underwood, FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther* 36: 911–919, 2006.

103. Pollard, CD, Sigward, SM, Ota, S, Langford, K, and Powers, CM. The influence of in-season injury prevention training on lower-extremity kinematics during landing in female soccer players. *Clin J Sport Med* 16: 223–227, 2006.

104. Pollard, CD, Sigward, SM, and Powers, CM. Gender differences in hip joint kinematics and kinetics during side-step cutting maneuver. *Clin J Sport Med* 17: 38–42, 2007.

105. Pollard, CD, Sigward, SM, and Powers, CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clin Biomech* 25: 142–146, 2010.

106. Prapavessis, H and McNair, PJ. Effects of instruction in jumping technique and experience jumping on ground reaction forces. *J Orthop Sports Phys Ther* 29: 352–356, 1999.

107. Prapavessis, H, McNair, PJ, Anderson, K, and Hohepa, M. Decreasing landing forces in children: The effect of instructions. *J Orthop Sports Phys Ther* 33: 204–207, 2003.

108. Quatman, CE, Ford, KR, Myer, GD, Paterno, MV, and Hewett, TE. The effects of gender and pubertal status on generalized joint laxity in young athletes. *J Sci Med Sport* 11: 257–263, 2008.

109. Quatman, CE and Hewett, TE. The anterior cruciate ligament injury controversy: Is "valgus collapse" a sex-specific mechanism?. *Br J Sports Med* 43: 328–335, 2009.

110. Reimer, RC III and Wikstrom, EA. Functional fatigue of the hip and ankle musculature cause similar alterations in single leg stance postural control. *J Sci Med Sport* 13: 161–166, 2010.

111. Ross, MD, Langford, B, and Whelan, PJ. Test–retest reliability of 4 single-leg horizontal hop tests. *J Strength Cond Res* 16: 617–622, 2002.

112. Self, BP and Paine, D. Ankle biomechanics during four landing techniques. *Med Sci Sports Exerc* 33: 1338–1344, 2001.

113. Sell, TC, Ferris, CM, Abt, JP, Tsai, YS, Myers, JB, Fu, FH, and Lephart, SM. The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism. *Am J Sports Med* 34: 43–54, 2006.

114. Shimokochi, Y and Shultz, SJ. Mechanisms of noncontact anterior cruciate ligament injury. *J Athl Train* 43: 396–408, 2008.

115. Sigward, S and Powers, CM. The influence of experience on knee mechanics during side-step cutting in females. *Clin Biomech (Bristol, Avon)* 21: 740–747, 2006.

116. Sigward, SM, Ota, S, and Powers, CM. Predictors of frontal plane knee excursion during a drop land in young female soccer players. *J Orthop Sports Phys Ther* 38: 661–667, 2008.

117. Söderman, K, Werner, S, Pietilä, T, Engström, B, and Alfredson, H. Balance board training: Prevention of traumatic injuries of the lower extremities in female soccer players? A prospective randomized intervention study. *Knee Surg Sports Traumatol Arthrosc* 8: 356–363, 2000.

118. Soligard, T, Myklebust, G, Steffen, K, Holme, I, Silvers, H, Bizzini, M, Junge, A, Dvorak, J, Bahr, R, and Andersen, TE. Comprehensive warm-up programme to prevent injuries in young female footballers: Cluster randomised controlled trial. *BMJ* 337: a2469, 2008.

119. Steffen, K, Myklebust, G, Olsen, OE, Holme, I, and Bahr, R. Preventing injuries in female youth football–A cluster-randomized controlled trial. *Scand J Med Sci Sports* 18: 605–614, 2008.

120. Tsai, LC, Sigward, SM, Pollard, CD, Fletcher, MJ, and Powers, CM. Effects of fatigue and recovery on knee mechanics during side-step cutting. *Med Sci Sports Exerc* 2009 [Epub ahead of print].

121. Weir, A, Darby, J, Inklaar, H, Koes, B, Bakker, E, and Tol, JL. Core stability: inter- and intraobserver reliability of 6 clinical tests. *Clin J Sport Med* 20: 34–38, 2010.

122. Wilderman, DR, Ross, SE, and Padua, DA. Thigh muscle activity, knee motion, and impact force during side-step pivoting in agility-trained female basketball players. *J Athl Train* 44: 14–25, 2009.

123. Willson, JD, Dougherty, CP, Ireland, ML, and Davis, IM. Core stability and its relationship to lower extremity function and injury. *J Am Acad Orthop Surg* 13: 316–325, 2005.

124. Withrow, TJ, Huston, LJ, Wojtys, EM, and Ashton-Miller, JA. The effect of an impulsive knee valgus moment on in vitro relative ACL strain during a simulated jump landing. *Clin Biomech (Bristol, Avon)* 21: 977–983, 2006.

125. Wojtys, EM, Huston, LJ, Schock, HJ, Boylan, JP, and Ashton-Miller, JA. Gender differences in muscular protection of the knee in torsion in size-matched athletes. *J Bone Joint Surg Am* 85: 782–789, 2003.

126. Zazulak, BT, Hewett, TE, Reeves, NP, Goldberg, B, and Cholewicki, J. Deficits in neuromuscular control of the trunk predict knee injury risk: A prospective biomechanical-epidemiologic study. *Am J Sports Med* 35: 1123–1130, 2007.

127. Zazulak, BT, Hewett, TE, Reeves, NP, Goldberg, B, and Cholewicki, J. The effects of core proprioception on knee injury: A prospective biomechanical-epidemiological study. *Am J Sports Med* 35: 368–373, 2007.

128. Zazulak, BT, Ponce, PL, Straub, SJ, Medvecky, MJ, Avedisian, L, and Hewett, TE. Gender comparison of hip muscle activity during single-leg landing. *J Orthop Sports Phys Ther* 35: 292–299, 2005.

129. Zebis, MK, Andersen, LL, Bencke, J, Kjaer, M, and Aagaard, P. Identification of athletes at future risk of anterior cruciate ligament ruptures by neuromuscular screening. *Am J Sports Med* 37: 1967–1973, 2009.

130. Zebis, MK, Bencke, J, Andersen, LL, Døssing, S, Alkjaer, T, Magnusson, SP, Kjaer, M, and Aagaard, P. The effects of neuromuscular training on knee joint motor control during sidecutting in female elite soccer and handball players. *Clin J Sport Med* 18: 329–337, 2008.

131. Zhang, LQ and Wang, G. Dynamic and static control of the human knee joint in abduction–adduction. *J Biomech* 34: 1107–1115, 2001.