Review

Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes

Gregory D. Myer1, Kevin R. Ford1, Timothy E. Hewett1,2

1Sports Medicine Biodynamics Center and Human Performance Laboratory, Division of Molecular Cardiovascular Biology, Cincinnati Children's Hospital Research Foundation, Cincinnati, OH, USA, 2College of Medicine, University of Cincinnati, Cincinnati, OH, USA

Corresponding author: Gregory D. Myer, MS, CSCS, Cincinnati Children's Hospital, 3333 Burnet Avenue, MLC 10001, Cincinnati, OH 45229, USA. Tel: +1-513-636-4366, Fax: +1-513-636-0516, E-mail: greg.myer@cchmc.org

Accepted for publication 08 June 2004

Female athletes have a four- to sevenfold increased risk of anterior cruciate ligament (ACL) injury compared with their male counterparts playing at similar levels in the same sports. The elevated risk of ACL injury in females coupled with the geometric increase in female sports participation in the last 30 years has led to a rapid rise in these injuries. This large increase in ACL injury incidence has fueled studies into both mechanisms of injury and interventions to prevent injury. A review of published multidisciplinary approaches demonstrates that several training protocols have utilized multiple components targeted toward injury prevention training and were able to reduce injury incidence in female athletes. Similar training techniques may also be used to gain improvements in measures of performance. The purpose of this review is to highlight training components that may reduce ACL injury risk and assess their potential for combined use in performance-oriented protocols.

Anterior cruciate ligament (ACL) injuries in the female athlete

Female athletes have a four- to sevenfold increased risk of ACL injury compared with their male counterparts playing at similar levels in the same sports (Malone et al., 1993; Arendt & Dick, 1995; Myklebust et al., 1998). The elevated risk of ACL injury in females coupled with the 900% increase in high school (NFHS, 2002) and 500% increase in collegiate (NCAA, 2002) sport participation in the last 30 years has led to a rapid rise in these injuries. This large increase in ACL injury incidence has fueled studies into both mechanisms and interventions to these debilitating sports injuries (Hewett et al., 1996, 1999; Wedderkopp et al., 1999; Soderman et al., 2000; Besier et al., 2001; Malinzak et al., 2001; Chappell et al., 2002; Ford et al., 2003; Myklebust et al., 2003). This paradigm shift of focus away from treatment and rehabilitation, toward injury mechanism and prevention is warranted, as reports from Scandinavia and the United States show that ligament injuries, specifically injury to the ACL are costly (de Loe et al., 2000), with conservative estimates of surgical and rehabilitative costs of $17,000 in US dollars per injury (Hewett et al., 1999). This is in addition to the potential loss of entire seasons of sports participation, scholarship funding, lowered academic performance (Freedman et al., 1998), long-term disability (Ruiz et al., 2002) and up to 105 times greater risk of radiographically diagnosed osteoarthritis to come in the future (Deacon et al., 1997). It would appear that the use of ACL injury prevention techniques would provide a sound time and financial investment for the coach, athlete, and sports medicine staff as the long-term costs of ACL injury may be significantly greater than the short-term costs.

The recent approaches to the design of neuromuscular training to prevent lower extremity injury have been diverse, utilizing many different types of training components. Review of the multidisciplinary approaches reported in the literature demonstrates that several training protocols have incorporated one or more components targeted toward injury-prevention training and were able to reduce injury incidence (Hejna et al., 1982; Caraffa et al., 1996; Lehnhard et al., 1996; Hewett et al., 1999; Heidt et al., 2000; Myklebust et al., 2003).

ACL injury-prevention studies

Hewett et al. (1996) initiated a program design that focused on correction of dynamic movement patterns and muscle imbalances that utilized technique training and lower body plyometrics with supplemental...
Myer et al.

strength training. These authors showed that female athletes who participated in a neuromuscular training program demonstrated greater dynamic knee control than females who had not undergone training. They were able to reduce knee varus/valgus moments with this type of neuromuscular training. An epidemiology study was also conducted with the purpose of prospectively evaluating the effects of the same neuromuscular training program on serious knee injury rates in female athletes. The incidence of serious knee injury was 0.43 in untrained females, 0.12 in trained females, and 0.09 in males (injuries/1000 exposures). Untrained females had a significantly higher incidence of serious knee injury than trained females and males. Training reduced non-contact ACL injuries to an even greater extent (Hewett et al., 1999). These results may indicate that the plyometric component of an exercise program, which trains the muscles, connective tissue and nervous system to effectively carry out the stretch-shortening cycle and that focus on proper technique and body mechanics, can reduce serious ligamentous injuries.

Training protocols that focused on resistance training alone have not been shown to reduce ACL injuries. However, there is inferential evidence that resistance training may reduce injury based on the beneficial adaptations that occur in bones, ligaments and tendons following training (Fleck & Falkel, 1986; Kraemer et al., 1998). Lehnhard et al. (1996) were able to significantly reduce injury rates with the addition of a strength-training regimen to a men's soccer team. They monitored injuries for 2 years without training and 2 years with the strength-training treatment added. While they did not specifically find a reduction of ACL injuries, they did report a decrease in percentage of injuries that were ligament sprains. The significant reduction of ligament sprains may have been related to reduced knee injury (43%) reported in the 2nd year of post-trained competition (Lehnhard et al., 1996). Additionally, Cahill and Griffith (1978) incorporated weight training into their pre-season conditioning for football teams. They found a reduction in reported knee injuries, and knee injuries that required surgery over four competitive seasons in the trained groups (Cahill and Griffith, 1978). Protocols that supplement plyometric and technique training with strength training may significantly reduce ACL injuries in female athletes (Hewett et al., 1999). Thus, it appears that resistance training is effective at reducing knee injuries when combined with other training components; however, the efficacy of a single-faceted resistance training protocol on ACL injury prevention is yet to be demonstrated in the literature.

Caraffa et al. (1996) prospectively evaluated the effect of balance board exercises on non-contact ACL injury rates in male athletes. The training consisted of approximately 20 min of balance board exercises divided into five phases. They compared athletes who participated in proprioceptive training prior to their competitive seasons vs. controls and found a significantly decreased rate of ACL injuries in the trained group (Caraffa et al., 1996). Similarly, a 5.9-time decrease in overall injury risk was achieved with balance training (Wedderkopp et al., 1999). Conversely, others have examined the effects of similar progressive balance board training and found no similar reduction of ACL injuries in female athletes (Soderman et al., 2000). Myklebust et al. (2003) examined the effects of a more comprehensive and dynamic neuromuscular training program. Their program elaborated on the balance board protocol of Caraffa et al. (1996) by adding a focus to improve awareness and knee control during standing, cutting, jumping, and landing. They demonstrated a reduction on the incidence of ACL injury in women's elite handball division over two competitive seasons (Myklebust et al., 2003). Others have shown that this type of proprioceptive and balance training can improve postural control and that lack of postural control, and stability were also related to increased risk of ankle injury (Tropp et al., 1984; Tropp & Odenrick, 1988; Holm et al., 2004). Likewise, improvement in single-leg stability can be gained with a neuromuscular training program that incorporates perturbations into balance training on unstable surfaces (Paterno et al., 2004). Balance training has also been shown to improve maximum lower extremity strength and decrease side-to-side imbalances in stabilometric measures (Heitkamp et al., 2001). Side-to-side imbalances in lower extremity surfaces has been shown to be a risk factor for ACL injury (Knapik et al., 1991). The literature discussed above supports integrating proprioceptive stability and balance training in ACL prevention protocols.

The effects of training, specifically targeted for speed enhancement on ACL injury risk reduction, have not been demonstrated. Heidt et al. (2000) were able to gain injury prevention effects through a speed-and-foot agility protocol. They were able to reduce lower extremity injuries in the trained female athletes by 19% when compared with the athletes who did not go through training. However, they did not find a statistically significant difference in ACL injuries between groups. They suggest that training protocols aimed at preventing injuries should focus on conditioning of the lower extremity in sport-specific activities (Heidt et al., 2000). Single-faceted sagittal plane treadmill training and conditioning protocols that do not incorporate sport-specific cutting maneuvers will not provide similar levels of external varus/valgus or rotational loads that are seen during sports competition (Lloyd & Buchanan,
Training programs that incorporate running and cutting with safe levels of varus/valgus stress may induce more muscle dominant neuromuscular adaptations to correct for “ligament dominance” in female athletes (Lloyd & Buchanan, 2001; Hewett et al., 2002). Such adaptations better prepare an athlete for more multidirectional sport activities and may reduce positioning that put high loads on the ACL (Lloyd & Buchanan, 2001).

Education and enforced awareness of dangerous positions and mechanisms of ACL injury have also been shown to decrease ACL injuries (Johnson, 2001). Ski instructors viewed videotapes of ACL injuries and were encouraged to formulate their own preventive strategies. ACL injuries were decreased by greater than 50% with this technique. Elements from this ski study should be applied to other sports. It is important to teach athletes to avoid biomechanically disadvantageous and dangerous positions in any sport. Henning identified three potentially dangerous maneuvers in basketball that he proposed should be modified through training to prevent ACL injury (Griffin & American Academy of Orthopaedic Surgeons, 2001). He suggested that athletes land in a more bent knee position and decelerate prior to a cutting maneuver. Preliminary work implementing the different techniques on a small sample of athletes showed a trend toward a decrease in injury rates between the trained vs. untrained study groups (Griffin & American Academy of Orthopaedic Surgeons, 2001). Hewett et al. (1999) expanded this concept and utilized a trainer to provide feedback and awareness to an athlete during training. Phrases such as “on your toes,” “straight as an arrow,” “light as a feather,” “shock absorber,” and “recoil like a spring” were used by the trainer as verbal and visualization cues for each phase of the jump. Each athlete was encouraged to do as many jumps as possible using the proper technique. As the athletes became fatigued, they were encouraged to stop if they could not execute each jump with correct biomechanics. Similarly, Myklebust et al. (2003) utilized partner training to provide the critical feedback. Partners encouraged each other to focus on the quality of their movements, specifically on the knee over the toe position. Both Hewett et al. (1999) and Myklebust et al. (2003) cited the critical analysis and feedback as contributors to the reduction of ACL injuries in their respective studies. These studies emphasize the importance of the analysis of the biomechanics of sports movements and constant and consistent feedback to the athlete regarding proper technique. A comprehensive overview suggests that several neuromuscular training components can provide some level of ACL, knee or lower extremity injury risk reduction. Selective combination of neuromuscular training components may provide additive effects, further reducing the risk of ACL injuries in female athletes.

Performance-enhancement studies

Neuromuscular training programs for young women can be effective at improving performance measures of speed, strength, and power (Kraemer et al., 1998; Wroble & Moxley, 2001; Kraemer et al., 2003). Female athletes may especially benefit from neuromuscular training, as they often display decreased baseline levels of strength and power compared with their male counterparts (Malina & Bouchard, 1991b; Hewett et al., 1996). Dynamic neuromuscular training has also been demonstrated to reduce gender-related differences in force absorption, active joint stabilization, muscle imbalances, and functional biomechanics while increasing strength of structural tissues (bones, ligaments, and tendons) (Fleck & Falkel, 1986; Rooks & Micheli, 1988; Faigenbaum et al., 1996; Hewett et al., 1996, 2004a; Myer et al., 2000). These ancillary effects of neuromuscular training, which likely reduce the risk of injury in female athletes, are positive results of training; however, without the performance enhancement training effects, athletes may not be motivated to participate in a neuromuscular training program. Prevention training that is oriented toward reducing ACL injuries in female athletes may have compliance rates as low as (28%) (Myklebust et al., 2003). However, training targeted toward improving measures of performance can have better compliance ranging from 80% to 90% (Ben-Sira et al., 1995; Kraemer et al., 1998; Wroble & Moxley, 2001; Hakkinen et al., 2003; Kraemer et al., 2003). Hence, if protocols were designed to focus on performance enhancement but incorporated proven ACL injury prevention techniques, combined performance and prevention training could be instituted on a widespread basis with potentially higher athlete compliance.

The effects of a sound resistance-training component on increases in strength in female athletes have widely been documented in the literature (Boyer, 1990; Fry et al., 1991; Ben-Sira et al., 1995; Chilibeck et al., 1998). Combining strength training with plyometrics may provide additional benefits. Subjects who underwent a combined plyometric and squat-training program had significant increases in vertical jump over subjects who only trained with squats or plyometrics alone (Adams et al., 1992). Additionally, Fatouros et al. (2000) found the combinatory effects of plyometrics and resistance training to not only increase jump performance but also leg strength.

Though the effects of core strength and balance training on measures of performance have not been
clearly demonstrated, the effects of these types of neuromuscular training are likely substantial (Heitkamp et al., 2001). Functional core strengthening and balance training can improve dynamic balance (Holm et al., 2004; Paterno et al., 2004). Increased dynamic balance may help provide the athlete with a dynamically stable core that can be more prepared to respond to the high forces generated at the distal body parts during athletic competition. These adaptations may reduce the risk of injury and prepare the athlete to achieve optimal performance. The global effects of core strength gains may be best attained with the incorporation of functional balance and core strengthening into several aspects of an athletes training program. The core muscles are “the most important non-specific muscle groups, which should be intentionally trained by young athletes regardless of sport” (Zatsiorsky, 1995).

Speed training enhances speed performance and plyometric or resistance training can provide compensatory effects for increasing speed (Delecluse et al., 1995; Reynolds et al., 2001). Young et al. (2001) found that sprint-training protocols that do not incorporate change-of-direction movements could improve straight-line speed, but not measures of agility. Conversely, change-of-direction training alone did not improve measures of straight line running (Young et al., 2001). The optimal method to maximize the effects of speed training to improve multidirectional speed related to sport may be to incorporate change-of-direction movements into speed training protocols.

Several types of training may provide the desired adaptations that can reduce ACL injury in female athletes (Caraffa et al., 1996; Hewett et al., 1999; Myklebust et al., 2003). It is also evident that measures of performance can be increased through single-component training targeted to improving desired measure in female athletes (Boyer, 1990; Ben-Sira et al., 1995; Chilibeck et al., 1998). Combining multiple components can provide additive and significantly greater performance effects than one-dimensional training (Adams et al., 1992; Delecluse et al., 1995; Fatouros et al., 2000; Reynolds et al., 2001; Young et al., 2001). Comprehensive neuromuscular training that combined plyometric/movement, core strengthening/balance, resistance and speed/agility training can improve several measures of performance concomitant with improved biomechanical measures related to ACL injury risk (Hewett et al., 2004a; Paterno et al., 2004). Adolescent female basketball, soccer, and volleyball players were evaluated prior to 6 weeks of comprehensive neuromuscular training. After training, the athletes demonstrated improved performance measures (back squat, single-leg hop and hold distance, vertical jump, speed), as well as several biomechanical factors related to injury risk (increased knee flexion–extension range of motion, decreased valgus moments during the landing phase of a vertical jump and improved single-leg dynamic stability) (Hewett et al., 2004a; Paterno et al., 2004). The results of these studies support the hypothesis that the combination of multiple injury prevention training components into a comprehensive program improves measures of performance and movement biomechanics.

Neuromuscular training conducted during adolescence increases neuromuscular function related to improved performance and to improved movement biomechanics that may be related to subsequent reduction of ACL knee injuries (Hewett et al., 1996, 1999, 2004c). However, it is not known who is in need of neuromuscular training and at what stage of maturation it should be used to maximize its effectiveness. Appropriately timed comprehensive neuromuscular training may be optimized if timed to precede or coincide with the growth spurt. Limiting the maturing athletes amount of exposure to high-risk competition, the effectiveness of neuromuscular training may be further increased.

**Timing of intervention**

Contrary to what is observed in the adolescent athlete, a thorough analysis of the published literature demonstrates no evidence that a difference in ACL injury rates exists in pre-pubescent athletes (Clanton et al., 1979; Gallagher et al., 1984; Buehler-Yund, 1999; Andrish, 2001). Knee injuries do occur in the pediatric athlete, as 63% of the sports-related injuries in children aged 6–12 years are classified as joint sprains and the majority of sprains occur at the knee (Gallagher et al., 1984). However, ACL sprains are more rare in pre-pubescent children than in adolescents and ACL ruptures do not present at significantly different rates in males and females prior to puberty (Clanton et al., 1979; Buehler-Yund, 1999; Andrish, 2001). Though equal numbers of ligament sprains occur in females and males prior to adolescence, females have higher rates immediately following their growth spurt and into maturity (Tursz & Crost, 1986).

While the biomechanics of growth and development show very similar trends between the genders, male and female neuromuscular patterns diverge significantly during and following puberty (Beunen & Malina, 1988; Malina & Bouchard, 1991b). Often, pubertal adolescents may demonstrate a decline in coordination and balance (Harris, 2000), as well as a distinct shift from risk of lower extremity fractures to increased likelihood of a ligament sprain (Adirim & Cheng, 2003). However, males demonstrate power, strength and coordination increases
Training to prevent ACL injuries in female athletes

Training timed with growth and development may induce the desired neuromuscular spurt that will decrease poor biomechanics and improve measures of performance (Myer et al., 2004). This may also help reduce the large rise in ACL injuries that has been shown to occur at age 12 (Shea et al., in press). Puberty coincides with the increased injury incidence at the same time that neuromuscular imbalances are initially demonstrated in young female athletes (Hewett et al., 2002, 2004a,b). A preemptive approach that institutes early interventional training may also reduce the peak rate of ACL injuries that occurs near age 16 in young girls (Shea et al., in press).

Practical perspectives: implications for protocol design and implementation

Neuromuscular training components that potentially elicit adaptations that will lead to reduction in ACL injury risk may be combined and provide additional improvements in performance (Hewett et al., 2004a,c). Pragmatic protocol design should include plyometrics and movement training, core strengthening and balance training, resistance training, and multidirectional interval speed training. Each component of the training should focus on comprehensive biomechanical analysis by the instructor with feedback given to the athlete both during and following training (Hewett et al., 2004a). The training protocol should stress technique perfection for each exercise, especially in the early training sessions. A trainer should be skilled in recognizing the desired technique for a given exercise and consistently encourage the athlete to maintain proper technique for as long as possible. If the athlete fatigues to a point that they cannot perform the exercise with near perfect technique, the exercise should be stopped. The goal of the next training session should then be to continue to improve technique, while increasing duration, volume or intensity of the exercise. The progressive nature of the neuromuscular training is important to achieve successful outcomes from the training (Hewett et al., 1996). Comprehensive neuromuscular training should stress performance of athletic maneuvers in a powerful, efficient and safe manner.

The plyometrics and dynamic movement training component should progressively emphasize double, then single-leg movements through training phases (Hewett et al., 1996). The majority of the initial exercises involve both legs to safely introduce the athletes to the training movements. Early training

with chronological age that correlate to maturational stage, while females on average show little change throughout puberty (Beunen & Malina, 1988; Malina & Bouchard, 1991b). No similar correlations between height, weight, and neuromuscular performance have been demonstrated in pubescent females. For example, vertical jump height (a measure of whole-body power) increases steadily in males during puberty, but not in females (Malina & Bouchard, 1991b; Kellis et al., 1999). Musculoskeletal growth during puberty, in the absence of corresponding neuromuscular adaptation, may facilitate the development of “neuromuscular imbalances” (Hewett et al., 2002), which may be displayed by decreased neuromuscular control of the knee joint (Hewett et al., 2004a,b). These developmental imbalances, if not addressed may continue through adolescence into maturity. Huston and Wojtys (1996) showed that collegiate-aged female athletes demonstrate neuromuscular recruitment and leg strength imbalances well past their developmental years. These imbalances may expose female athletes, especially elite athletes, to increased risk during multiple years of athletic participation.

Movement biomechanics and lower extremity strength can be altered in adolescent females with neuromuscular training (Hewett et al., 1996). Neuromuscular power can increase within 6 weeks of training and may result in significant decreases in peak impact forces and abduction torques at the knee (Hewett et al., 1996). Observed increases in females may be greater than in males as their baseline neuromuscular performance levels are lower on average (Kraemer et al., 2001). Dynamic neuromuscular training may reduce ACL injuries in adolescent (Hewett et al., 1999) and mature female athletes (Myklebust et al., 2003). In addition, neuromuscular training may induce measures of the “neuromuscular spurt” in females (Tropp & Odenrick, 1988; Malina & Bouchard, 1991a; Hewett et al., 1996; Kraemer et al., 2001). Intensive neuromuscular training significantly increases fat-free mass, vertical jump height, and balance measures in adolescent females (Tropp & Odenrick, 1988; Hewett et al., 1996; Kraemer et al., 2001). Likewise, pre-pubertal athletes can improve lower extremity strength and power through short-term resistance training (Faigenbaum et al., 1999) and sport-specific training, respectively (Bencke et al., 2002). Targeted neuromuscular training, at or near the onset of puberty, may simultaneously improve lower extremity strength and power, reduce dangerous biomechanics related to ACL injury risk and improve single-leg balance (Hewett et al., 2004c; Myer et al., 2004). These reports suggest that the benefits of neuromuscular training may be advocated to pre and early pubertal children.
emphasis should be on sound athletic positioning that can help create dynamic control of the athlete’s center of gravity (Myklebust et al., 2003). Soft, athletic landings that stress deep knee flexion should be employed by the trainer with verbal feedback to make the athlete aware of biomechanically unsound and undesirable positions. Progressively, a greater number of single-leg movements can be introduced, while the focus on correct technique must be maintained. For example, the single-leg crossover hop and hold exercise can be used as an important exercise to teach single-leg landings (Fig. 1). Later training sessions can utilize explosive double- and single-leg movements which focus on maximal performance in multiple planes of movement. Volume of the initial plyometric bouts should be low due to extensive technique training that is required and decreased ability of the athlete to perform the exercise with proper technique for the given durations. Volume can be increased as technique improves to the mid-point of training, after which a progressive decrease in volume is followed for the final sessions to allow for increased training intensity (Hewett et al., 1996).

The final progressions of the plyometric and movement training should utilize unanticipated cutting movements during training. Single-faceted sagittal plane training and conditioning protocols that do not incorporate cutting maneuvers will not provide similar levels of external varus/valgus or rotational loads that are seen during sport-specific cutting maneuvers (Lloyd & Buchanan, 2001). Training programs that incorporate safe levels of varus/valgus stress may induce more “muscle-dominant” neuromuscular adaptations. Such adaptations can better prepare an athlete for more multidirectional sport activities, which can improve their performance and reduce risk of lower extremity injury (Cahill & Griffith, 1978; Hewett et al., 1996, 1999). Female athletes perform cutting techniques with decreased knee flexion and increased valgus angles (Malinzak et al., 2001). Knee valgus loads can double when performing unanticipated cutting maneuvers similar to those utilized in sport (Besier et al., 2001a). The endpoint of training designed to reduce ACL loading via valgus torque reduction may be gained through training the athlete to use movement techniques that produce low abduction knee joint moments (Besier et al., 2001a, b). Training which incorporates unanticipated cuts reduces knee joint loads (Hewett et al., 2004a). Additionally, by improving reaction times to

---

**Fig. 1.** Crossover hop, hop, hop, stick: In this exercise, the athlete starts on a single limb and jumps at a diagonal across the body landing on the opposite limb with the foot pointing straight ahead and immediately redirects the jump in the opposite diagonal direction. Train this jump with care to protect your athlete from injury.

**Fig. 2.** Athletic position: Athletic position is a functionally stable position with the knees comfortably flexed, shoulders back, eyes up, feet approximately shoulder-width apart and the body mass balanced over the balls of the feet. The knees should be over the balls of the feet and chest should be over the knees.
provide more time to voluntarily pre-contract musculature and make appropriate kinematic adjustments, ACL loads may be reduced (Neptune et al., 1999; Besier et al., 2001a).

Prior to teaching unanticipated cutting, athletes should first be able to attain proper athletic position proficiently (Fig. 2). The athletic position is a functionally stable position with the knees comfortably flexed, shoulders back, eyes up, feet approximately shoulder-width apart and the body mass balanced over the balls of the feet. The knees should be over the balls of the feet and chest should be over the knees (Hewett et al., 1996). This is the athlete-ready position and should be the starting and finishing position for most of the training exercises. This is the goal position prior to initiating a directional cut. Adding the directional cues to the unanticipated part of training can be as simple as the trainer pointing out a direction or as sports-specific as using partner mimic or ball retrieval drills. Training the athlete to employ safe cutting techniques in unanticipated sport situations may instill technique adaptations that will more readily transfer onto the field of play. The “ligament-dominant” athlete may become muscular-dominant if these adaptations are achieved, which may reduce their future risk of ACL injury (Hewett et al., 1996, 1999, 2004c).

The resistance-training component of the protocol should be progressive with an initial high-volume, and low-intensity protocol (Kraemer et al., 1998; Wroble & Moxley, 2001; Kraemer et al., 2003). The initial training intensity should be set at approximately 60% of the athlete’s pre-tested predicted one repetition maximum. Exercise selection order should progress from multijoint exercises to alternating upper and lower body exercises. Trainers should take the time to prescribe the weight to be used prior to each training session based on the workload accomplished in the prior session for each athlete. The weight used must be increased prior to each training session, if the required number of repetitions was achieved to ensure that appropriate intensity progressions occur. The emphasis for intensity selection is proper technique and safety. If technique is not near perfect, then weight should be lowered until proper technique can be restored. The assisted Russian hamstring curl is an important exercise that should be included in the training to focus on correcting the low hamstring strength and recruitment levels common to female athletes (Hewett et al., 1996; Huston & Wojtys, 1996). Figure 3 shows the trainer-assisted performance of this training technique. The goal of the resistance-training component of the protocol is to strengthen all major muscle groups through the complete range of motion and to provide complimentary muscular power to the plyometric and speed components of the protocol.

The core-strengthening and balance-training component of the protocol should follow an organized exercise selection specifically directed at strengthening the core stabilizing muscles. This component is focused on providing an appropriate balance between developing the proprioceptive abilities of the athlete and exposing the athlete to inadequate joint control. The training progressions should take the athlete through a combination of low- to higher-risk maneuvers in a controlled situation. The intensity of the exercises can be modified by changing the arm position, opening and closing eyes, changing support stance (Fig. 4), increasing or decreasing surface stability with balance-training device (Fig. 5), increasing or decreasing speed, adding unanticipated movements or perturbations, and adding sports-specific skills. The goal of the functional balance training and core strengthening is to bring the athlete to a level of core stability and coordination that allows them to properly reduce force, maintain balance and posture, and subsequently regenerate force in the desired direction.

The speed component of training can be accomplished through interval resistive band running or high-intensity treadmill training (Mero & Komi, 1986; Corn & Knudson, 2003). The important component to maintain is the interval portion with short duration and high-intensity bouts. Performing excessive endurance training may interfere with explosive strength development (Hakkinen et al., 2003). To perform the interval partner-resistive band running, two pliable bands (e.g., medium bands-Jump Stretch Inc., Youngstown, OH, USA) can be tied together and anchored around the waist of partnered athletes (Fig. 6). The athlete in the forward position should be instructed to very quickly transition from this...
starting stance to run with proper biomechanics for the allotted time period. The trailing athlete provides a light, medium or heavy resistance as instructed by the trainer. During the initial session, the athletes should be instructed by the trainers on how to vary the desired resistance. Trainers provide biomechanical feedback during each training bout. The final run of each session should include a non-resisted maximum effort run of varying distance. If available, speed training can be performed on high-performance treadmills which can accommodate high speeds and inclines that allow easy modification of protocol intensity (Mero & Komi, 1986). The goals of the interval speed-training component are to improve running mechanics, short distance speed, explosiveness, and increased muscular resistance to fatigue.

Conclusions

In conclusion, there is strong evidence that neuromuscular training that selectively combines several components, not only decreases the potential biomechanical risk factors of lower extremity injury, but also provides performance enhancement effects. It appears that the effects of plyometric power, strength, core stability and speed may provide synergistic effects in female athletes. By addressing aspects of injury prevention and athletic performance with a
protocol targeted toward pubertal athletes, females may have the potential to achieve optimal performance during injury-free sports participation.

**Training to prevent ACL injuries in female athletes**

**Key words:** neuromuscular training, balance training, strength, plyometrics, speed training, knee, injury prevention, gender differences.

**References**


Myer et al.


Shea KG, Pfeiffer R, Wang JH, Curtin M, Apel PJ. Anterior cruciate ligament