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REVIEW

A review of electromyographic activation levels, timing differences, and increased anterior cruciate ligament injury incidence in female athletes

T E Hewett, B T Zazulak, G D Myer, K R Ford

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Deficits in dynamic neuromuscular control of the knee may contribute to the higher incidence of anterior cruciate ligament (ACL) injury in female athletes. There is evidence that neuromuscular training alters muscle firing patterns, as it decreases landing forces, improves balance, and reduces ACL injury incidence in female athletes. The purpose of this review is to summarise the evidence for altered muscular activation and timing relative to ACL injury risk in female athletes.

risk of injury.⁹ Female subjects show greater dynamic lower extremity valgus (hip adduction and internal rotation, knee abduction, tibial external rotation, and possibly forefoot pronation).^{11–15}

Altered neuromuscular timing and recruitment may lead to the aforementioned dynamic lower extremity valgus observed in women.^{11–15} Measures of dynamic valgus predict non-contact ACL injury risk in female athletes with an accuracy approaching 90%.¹ Computer simulation modelling demonstrates that lower extremity valgus loads at the knee are high enough to rupture the ACL, whereas knee extension and anterior shear loads alone are not sufficient to rupture the ligament.¹⁵

Dynamic neuromuscular restraints to lower extremity joint motion include both feed forward and feedback motor control loops.¹⁶ Feed forward neuromuscular control, developed during previous movement, may activate muscles around the joint before excessive loading in order to absorb force and decrease stress on the ligaments.¹⁷ Feedback or reactive motor control strategies alter muscle activation in response to situations that load the lower extremity joints.¹⁸ Female subjects may display a longer latency period—that is, electromechanical delay—between preparatory and reactive muscle activation.¹⁹ Preparatory muscle activity can stiffen joints before unexpected perturbations.^{17 18 20 21} Neuromuscular training that reproduces loads similar to those encountered during competitive sports may assist in the development of both feed forward and reactive muscle activation strategies that protect the knee joint from excessive load.^{18 19 21–24} Plyometric exercises subject the joint to rapid loads and can activate preparatory and feedback motor control loops by adaptation of the muscle stretch receptors.²⁵ Balance and core stability exercises force the athlete to pre-tense the musculature and rapidly react to motion or perturbation.

If neuromuscular training can increase neuromuscular control of the joint and decrease knee and ACL injury risk, it is likely that the mechanisms underlying increased risk are neuromuscular in nature. Several prospective studies have shown that neuromuscular training has the potential to decrease knee injuries in general, and ACL injuries in particular, in athletes.^{26–30} Intensive short term neuromuscular

Deficits in dynamic neuromuscular control of joint stability in all three axes of motion (proximal-distal, anterior-posterior, medial-lateral) along the entire lower extremity kinetic chain may contribute to differences in anterior cruciate ligament (ACL) injury rates between female and male athletes. Although the 4–6-fold higher incidence of ACL injuries in female athletes is well established, the underlying neuromuscular mechanisms that account for this are not completely delineated. The contribution of relative muscle activation levels to this important clinical dilemma is especially unclear. Lack of dynamic neuromuscular control of the knee (active restraint) is an important contributor to ACL (passive restraint to tibial translation) injury in female athletes.¹ ACL injury occurs under conditions of high dynamic loading of the knee joint, when active muscular restraints do not adequately dampen joint loads and the passive restraints are subjected to increased loads.² Decreased neuromuscular control of the joint may place increased stress on the passive ligament structures that exceed the failure strength of the ligament.^{3 4} Neuromuscular recruitment patterns that compromise active joint restraints subject passive joint restraints to greater load, decrease dynamic knee stability, and increase risk of ACL injury.^{3 5}

Female athletes display different neuromuscular strategies from male athletes.^{6–9} These sex differences in muscle recruitment and timing of muscle activation may affect dynamic knee stability. Neuromuscular preplanning allows feed forward recruitment of the musculature that controls knee joint positioning during landing and pivoting manoeuvres.¹⁰ Imbalanced or ineffectively timed neuromuscular firing may lead to limb positioning during athletic manoeuvres that puts the female ACL under increased strain and

See end of article for authors' affiliations

Correspondence to:
Dr Hewett, Cincinnati
Children's Hospital, Sports
Medicine Biodynamics
Center, Cincinnati, OH
45229, USA; tim.hewett@cchmc.org

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Abbreviations: ACL, anterior cruciate ligament; EMG, electromyographic

training may induce a “neuromuscular spurt” that may otherwise be absent in adolescent females.^{13 31–33} Training and strength differences may account for only a portion of the higher incidence of knee injury in female athletes, but lowering these high figures by even a small percentage could have a significant effect on the number of knee injuries in female athletes. Such training, if effectively implemented on a widespread basis, may help to considerably decrease the number of athletes injured each year.

The purpose of this review is to summarise the evidence for altered muscular activation and timing relative to ACL injury risk in female athletes.

DIFFERENCES IN ELECTROMYOGRAPHIC (EMG) ACTIVATION LEVELS BETWEEN MALE AND FEMALE ATHLETES

Proximal

Asymmetry of proximal muscle activation may alter the position of the knee during landing and cutting in female athletes. Decreased activation of the trunk and hip musculature may lead to lower extremity malalignment. Decreased activation of proximal stabilising muscles may lower load bearing capacity of the knee joint. Lephart *et al*¹⁶ report that female subjects have increased hip internal rotation during landing. Increased hip internal rotation and valgus may increase strain on the ACL.^{2 34} Zazulak *et al*⁸ report lower gluteal EMG activity in women than men during landing (figs 1 and 2). The proximal stabilising muscles, specifically the gluteals, control lower limb position, energy absorption, and function as powerful extensors, external rotators, and abductors of the hip during landing.^{8 35}

Chimera *et al*³⁶ evaluated the effects of plyometric training on muscle activation patterns during jump exercise and reported increased firing of the hip adductor muscles during the pre-landing phase. The experimental group showed greater preparatory adductor to abductor muscle activation. Hewett *et al*³¹ showed significant decreases in abduction/adduction moments after plyometric training. These findings delineate the role of hip muscle activation in dynamic restraint and control of lower extremity alignment.

Anterior-posterior

Female athletes show increased activation of the quadriceps relative to the antagonistic hamstring musculature.^{14 31 37} This disproportional recruitment of the vastus musculature increases anterior shear force at the low knee flexion angles that occur during high risk landing and pivoting

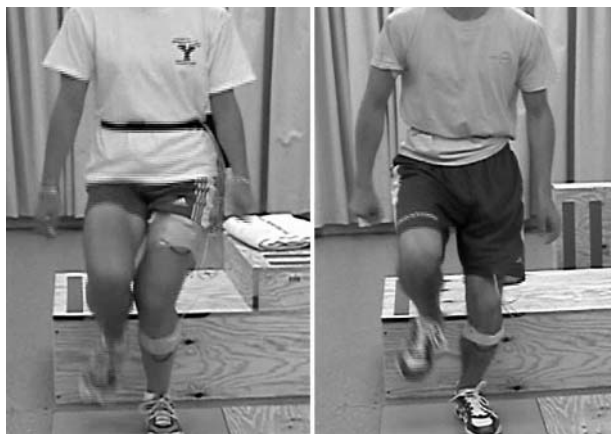


Figure 1 Visual representation of the landing manoeuvre tested in the study. Female (left) and male (right) subjects completing drop landings from 30.5 cm box heights. Patient consent was obtained for the publication of this figure.

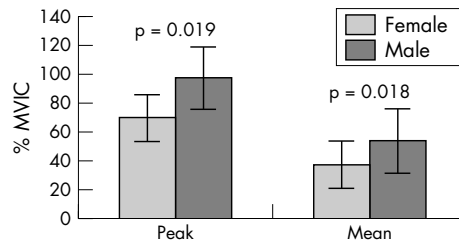


Figure 2 Gluteus maximus post-contact ensemble peak and mean electromyographic values in female and male subjects. Values are mean ± 1.96 SE. MVIC, Maximal voluntary isometric muscular contraction.

movements.^{9 34} The quadriceps, through the anterior pull of the patellar tendon on the tibia, contribute to ACL loading when knee flexion is less than 30°.^{34 38} Muscular co-contraction compresses the joint, due in part to the concavity of the medial tibial plateau, which may protect the ACL against anterior drawer.³⁹

Zazulak *et al*⁸ reported greater peak quadriceps activity in female than male subjects (fig 3). Decreased balance in strength and recruitment of the flexor relative to the extensor musculature may put the ACL at greater risk.³¹ Adequate co-contraction of the knee flexors is needed to balance contraction of the quadriceps, compress the joint, and control high knee extension and abduction torques.³¹ Appropriate hamstrings recruitment may prevent the critical loading necessary to rupture the ACL during manoeuvres that place the athlete at risk of an injury.

Medial-lateral

Joint compression through muscular co-contraction allows valgus load to be carried by articular contact forces, protecting the ligaments. Decreased medial joint compression may limit passive resistance to dynamic knee valgus, predisposing the female knee to medial femoral condylar lift off and increased loads on the ACL.^{12 40 41} Rozzi *et al*⁶ reported that female athletes show a disproportionate (4 times greater) firing of their lateral hamstrings during landing. Myer *et al*⁹ showed a decreased ratio of medial to lateral quadriceps recruitment in female subjects (fig 4). The decreased ratio combined with unbalanced medial hamstrings recruitment may decrease control of coronal plane forces at the knee.^{6 34 40} Markolf *et al*³⁴ showed that muscular contraction can decrease both the valgus and varus laxity of the knee threefold. A low ratio of medial to lateral quadriceps recruitment combined with increased lateral hamstring firing may compress the lateral joint, open the medial joint, and increase anterior shear force, which directly loads the ACL.^{6 34 42}

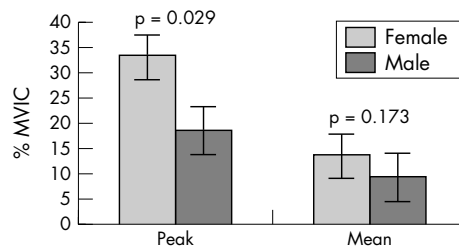


Figure 3 Rectus femoris pre-contact ensemble peak and mean electromyographic values in female and male subjects. Values are mean ± 1.96 SE. MVIC, Maximal voluntary isometric muscular contraction.

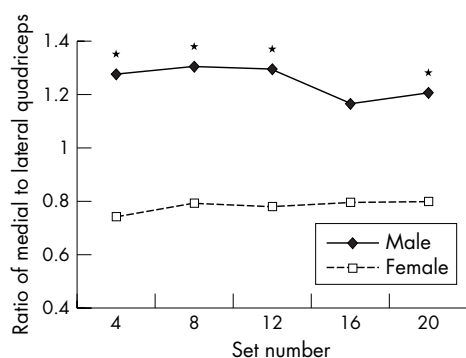


Figure 4 Root mean square ratio of medial to lateral quadriceps activation during performance of exercise sets. Female subjects displayed significantly decreased medial/lateral quadriceps activation. Reproduced, with permission, from Myer *et al.*⁹

Distal

Calf and ankle muscle recruitment may play a role in dynamic stabilisation of the knee joint. Besier *et al.*¹⁰ reported selective activation of medial knee musculature, including the medial gastrocnemius, during sidestep tasks with valgus and external rotation moments. Nyland *et al.*⁴³ concluded that the gastrocnemius provided synergistic and compensatory dynamic knee stabilisation with quadriceps fatigue. ACL deficient female subjects showed decreased preactivation of the lateral gastrocnemius.⁴⁴

Shultz *et al.*⁴⁵ evaluated the protective neuromuscular response and activation patterns to an imposed perturbation during weight bearing stance—that is, a sudden forward and either internal or external rotation moment of the trunk and femur. The gastrocnemius fired faster than the hamstring, which fired faster than the quadriceps. This activation pattern is similar to the postural response reported by Nashner,⁴⁶ specifically a distal to proximal firing pattern, with the distal muscles preceding the proximal muscles by 10–15 milliseconds.

TIMING OF MUSCLE FIRING

EMG studies show sex related differences in the timing of muscle activation during athletic movement.^{6 8–10 37 47 48} Zazulak *et al.*⁸ reported increased peak quadriceps activity in female subjects during the pre-contact phase of landing. Greater rectus femoris activity was observed in female than male subjects (fig 3). This increased activation of rectus femoris may increase strain on the ACL during landing. Increased quadriceps activity combined with decreased hamstring activity may decrease kinetic energy absorption during landing and may increase ground reaction forces and torques associated with ACL injury.

Wojtys *et al.*³⁷ reported that female athletes have a slower response of hamstring activation to anterior stress on the ACL. Cowling and Steele⁴⁸ reported sex differences in muscle activation strategies in the hamstrings musculature that contradict the findings of Wojtys *et al.* Male subjects were found to activate their semi-membranosus muscle later than female subjects in the pre-landing phase and reach peak activity sooner.⁴⁸ Besier *et al.*¹⁰ examined a sidestep cut at two different angles under both preplanned and unanticipated conditions. They found increased varus/valgus and internal/external knee moments during unanticipated movements and suggested that there may be increased potential for non-contact knee injuries during unanticipated sport movements.

Lower extremity muscle activation during cutting may be different between preplanned and unanticipated conditions.⁴⁷ Besier *et al.*¹⁷ also reported that activation patterns during

cutting manoeuvres are preplanned to counter loading in response to varus/valgus and internal/external rotation moments at the knee. The unanticipated sidestep condition was reported to increase muscle activation 10–25%, with the greatest increase before initial contact.⁴⁷ ACL injuries occur too quickly for reflexive or voluntary muscular activation. However, preactivation may reduce the probability of injuries caused by unexpected perturbations. The lower extremity musculature may be 40–80% activated at the time that the foot touches the ground.⁴⁹

SUMMARY AND CONCLUSIONS

Differences are observed in male and female EMG firing patterns. Decreased neuromuscular control of the trunk and lower extremity in women may increase the potential for valgus lower extremity position and increased ACL injury risk. Identification of these neuromuscular imbalances has potential for both screening of high risk athletes and targeting interventions to specific deficits. Dynamic neuromuscular training can increase active knee stabilisation and decrease the incidence of ACL injury in the female athletic population.^{26 31 50 51} Training may facilitate neuromuscular adaptations that provide increased joint stabilisation and muscular preactivation and reactive patterns that protect the athlete's ACL from increased loading.^{50 52 53}

In conclusion, there is evidence that neuromuscular training alters muscle firing patterns as it decreases landing forces, improves balance, and reduces ACL injury incidence in female athletes. Future approaches could be to use EMG analysis to assess the relative efficacy of these interventions in order to achieve the optimal effect in the most efficient manner possible. Selective combination of neuromuscular training components may provide additive effects, further reducing the risk of ACL injuries in female athletes. Additional research directions include the assessment of relative injury risk using mass neuromuscular screening. The development of screening and intervention protocols may lead to the reduction of ACL injury incidence in female athletes through the identification of the high risk female athlete subgroup that displays decreased hip and increased quadriceps muscle firing, and the correction of these neuromuscular control deficits.

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Authors' affiliations

T E Hewett, G D Myer, K R Ford, Cincinnati Children's Hospital, Sports Medicine Biodynamics Center, Cincinnati, OH, USA

B T Zazulak, Department of Rehabilitation Services, Yale-New Haven Hospital, New Haven, CT, USA

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