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Sex Differences in Proximal Control of the Knee Joint

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Abstract

Following the onset of maturation, female athletes have a significantly higher risk for anterior cruciate ligament (ACL) injury compared with male athletes. While multiple sex differences in lower-extremity neuromuscular control and biomechanics have been identified as potential risk factors for ACL injury in females, the majority of these studies have focused specifically on the knee joint. However, increasing evidence in the literature indicates that lumbopelvic (core) control may have a large effect on knee-joint control and injury risk. This review examines the published evidence on the contributions of the trunk and hip to knee-joint control. Specifically, the sex differences in potential proximal controllers of the knee as risk factors for ACL injury are identified and discussed. Sex differences in trunk and hip biomechanics have been identified in all planes of motion (sagittal, coronal and transverse). Essentially, female athletes show greater lateral trunk displacement, altered trunk and hip flexion angles, greater ranges of trunk motion, and increased hip adduction and internal rotation during sport manoeuvres, compared with their male counterparts. These differences may increase the risk of ACL injury among female athletes. Prevention programmes targeted towards trunk and hip neuromuscular control may decrease the risk for ACL injuries.

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1. Introduction

The number of females participating in sports has increased by over 900% in high school and 500%^[1] in collegiate athletics over the last few decades. This large increase in participation, combined with a 4- to 6-fold higher anterior cruciate ligament (ACL) injury rate in females^[2-4] has led to a corresponding increase in ACL injuries. ACL ruptures lead to chronic knee pain and disability, a significantly greater risk of radiographically diagnosed knee osteoarthritis,^[5-8] high costs for management,^[9-12] loss of entire sports seasons, possible loss of scholarship funding and significantly lowered academic performance.^[13,14]

Sex differences in ACL injury rates may be explained by anatomical,^[15-23] hormonal^[4,7,24-30] and/or neuromuscular factors.^[11,31-34] Even though anatomical and hormonal factors may contribute to an ACL injury, the implications of both factors are not yet clear.^[35] Moreover, modification of these parameters would be both difficult and controversial. In contrast, neuromuscular adaptations are readily achievable and have been used extensively to lower ACL injury risk in female athletes.^[7,33,36-38]

There is increasing evidence that insufficient or abnormal neuromuscular control of the lower limbs during athletic movements, in particular over the knee joint, is a primary contributor to non-contact ACL injuries, especially in the female athlete.^[39] The knee is not an isolated joint, but is part of the body in which the trunk, hips, knees and ankles constitute the body's kinetic chain that controls lower-extremity movements. The proximal and distal segments of the body's kinetic chain can have significant effects on knee-joint biomechanics.^[35,37] The kinetic chain model refers to the body as a linked system of interdependent segments, often working in a proximal-to-distal sequence, to achieve the desired movement in an efficient manner.^[40] Hence, considering the relationship between the trunk and the lower-extremity joints during a dynamic task, it is important to consider the effects of the trunk and hip on the control of the knee. Specifically, the trunk-to-hip system will be referred to as core, throughout the review. This review reports the existing evidence on the contributions of the trunk and hip to neuromuscular control of the knee joint.

A systematic review of the literature was performed by utilizing an electronic database literature search in PubMed MEDLINE (1985–2009). The keyword selection was designed to capture all aspects of the contributions of the trunk and hip to neuromuscular control of the knee joint and the search terms included: 'ACL prevention', 'ACL biomechanics', 'ACL and trunk', 'ACL and hip', 'non-contact ACL injuries', 'mechanisms of ACL injuries' and 'prevention non-contact ACL injuries'. The search was supplemented by a review of the bibliographies of retrieved articles, personal correspondence with authors of retrieved articles and hand searching of journals to identify any additional studies addressing this topic of interest. Articles included in this review were limited to those published in English.

2. The Concept of 'Core Stability'

Despite the growing interest in the body's core during the last decade, 'core stability' remains an often ambiguous or misused term. It has been incorrectly used synonymously and interchangeably with core strength, hip strength, balance and spine stability. In this

review, the term ‘core musculature’ will be referred to as those muscles that surround and insert into the lumbopelvic region. These muscles act synergistically to stabilize the trunk and hip and contribute to the stability of more distal joints, including the knee joint. The term ‘core stability’ is considered the ability of passive (ligaments and vertebral facets) and active stabilizers involved in the lumbopelvic region to maintain appropriate trunk and hip posture, balance and control during static and dynamic movements.^[41] Neuromuscular control consists of sensory input (muscle spindles, Golgi tendon organs and receptors within the core ligaments),^[42,43] CNS processing and motor (the neuromuscular signal) output. The output is targeted to the core musculature, thus optimal recruitment, strength and endurance of the 29 muscles attached to the pelvis are necessary to maintain and restore joint (core) homeostatic stability in response to internal or external forces from expected or unexpected perturbations in all planes of motion. The need for an adequate intermuscular coordination between such a large number of muscles shows the complex nature existing under the concept of core. Core stability, a critical component of the entire body kinetic chain, is especially important during unexpected dynamic situations, where insufficient control of the core may affect the control of other joints through the multi-segment system and possibly lead to injury at other joints in the system.^[39] The concepts of ‘robustness’ and ‘performance’ are important for the proper investigation of dynamic stability of the core during athletic manoeuvres.^[44] According to the definition of robustness of Reeves et al., the core is considered to be robust if it remains stable after perturbation.^[44] In contrast, performance is defined as how close the disturbed trajectory of the core remains to the undisturbed and expected trajectory. Both concepts depend on the neuromuscular control of all the muscles that attach to the lumbopelvic region.

The main function of the core during sports manoeuvres is to maintain the stability of the whole system and allow optimal production, transfer and control of force and motion to the terminal segment (proximal to distal) for integrated kinetic chain activities in order to achieve the maximum efficiency.^[45] Kibler et al.^[45] demonstrated that >50% of the total kinetic energy and total force generated in the tennis serve is generated by the lower legs, hip and trunk. The proximal to distal muscle firing sequence has been shown in running and kicking activities, with the hip flexors being the main contributor muscles to achieve the highest velocities.^[40,46]

Growing evidence for decreased neuromuscular control of the core as an underlying cause of injury^[41,47–53] justifies the increased use of current trunk or core neuromuscular training as a central tenet of rehabilitation treatments and prevention.^[54–59] However, some of these studies observed a reduction of force output at the hip, which may consequently result in an increased risk of lower-extremity injury. Although the hip is part of the core, measures of hip strength should not be wholly defined as, or generalized to, core stability. It is not known how isolated hip strength functions to stabilize the core. If quantitative analysis is accurate, for daily living, 10% of maximal voluntary contraction or even less of abdominal co-contraction may be sufficient to achieve spine stability. Moreover, given the relationship observed between stiffness and stability, the majority of spine stability may be achieved in the first 25% of the maximum contraction level.^[60] Hence, neural control, motor firing patterns or muscular endurance are likely to be of greater importance than strength in determining overall core stability. Further studies and the use of core models that include all

the muscles that attach to the pelvis are needed to elucidate the influence of each of these control components on total core stability. Ireland^[61] speculated about a possible relationship between the trunk and hip with ACL injuries. The videographic sequence analyses of sports knee injuries formed the basis of the authors' proposed 'position of no return' model for a non-contact ACL injury.^[61] However, the link between proximal control strategies and abnormal knee-joint loading and motions specifically related to sex differences remains unclear.

In the remainder of this review, we evaluate the current evidence into the three planes of movement (sagittal, coronal and transverse) in order to create a working construct to better understand the current evidence for the connection between the proximal core neuromuscular controllers and distal knee-joint stability. Although trunk and hip are part of the core, both regions were reviewed in separate sections for didactic reasons.

In summary:

- Core musculature is referred to as those muscles that surround and insert into the lumbopelvic region.
- These muscles act synergistically to stabilize the trunk and hip and contribute to the stability of more distal joints, including the knee joint.
- Core stability is considered the ability of passive and active stabilizers of the lumbopelvic region to achieve the minimum neuromuscular control needed, in order to maintain appropriate trunk and hip posture, balance and control during static and dynamic movements.
- The link between proximal control strategies and abnormal knee-joint loading and motions specifically related to sex differences remains unclear.

3. Sagittal Plane Evidence for Proximal Control of Knee-Joint Stability

3.1 Trunk Contributions

Knee flexion-extension may be influenced by the trunk and hip proximal musculature. The trunk, arms and head comprise approximately 60% of the body mass.^[62] Increases in height of the centre of mass during puberty may result in more challenging trunk neuromuscular control, especially during high-speed athletic manoeuvres.^[63] Trunk, arms and head position relative to hip, knee and ankle may influence ground reaction force (GRF), energetics and knee load from a landing or cutting manoeuvre.^[64] An understanding of the biomechanical relationship between the trunk and knee may be used to reduce GRF and energetic demands of passive and dynamic restraints and thus decrease the likelihood of knee injury.

Recently, Blackburn and Padua studied trunk, hip and knee biomechanics during two landing tasks, a natural landing strategy (preferred) and a landing that involved active trunk flexion upon landing (flexed). Peak trunk flexion angle was 47% greater for the flexion group compared with the preferred landing group.^[65] The authors demonstrated that trunk flexion during landing produced concomitant increases in knee (22°) and hip flexion (31°) angles. An increase in knee flexion may result in decreased anterior shear forces and GRF, with a subsequent decrease in ACL load. Hamstrings lengthening and the increase in passive

tension imposed by greater hip flexion may also account for the decreased tension induced by knee flexion. Coronal and transverse plane knee kinematics did not differ significantly between preferred and flexed landings. In addition, the authors did not find sex differences in landing forces and quadriceps electromyographic activity depending on trunk flexion.^[66] Flexing the trunk forward or moving the mass of the upper body anterior towards the knees may result in a reduced external knee flexion and internal quadriceps moments with concomitant increase in internal hamstrings moments during landing. This may be explained by a reduction in the quadriceps moment arm (decreasing shear forces) between trunk and knee, and an increase in the hamstrings hip extensor activity.^[64] Synergistically, trunk flexion in a standing position may increase posterior shear forces and enhance hamstrings activation, which can potentially decrease forces on the ACL.^[67,68] This mechanical advantage can be altered by reduced stiffness derived by excessive length and laxity of hamstrings muscles. Increased laxity may reduce muscle reflex activity and fibre shortening velocity.^[69,70] Both would increase latencies, decrease joint stiffness and potentially decrease dynamic knee stability.^[31,69–76] Generalized joint laxity, which has been reported to be higher in female athletes, and anterior–posterior knee-joint laxity have been associated with an increased risk of non-contact ACL injury for both males and females.^[77–80]

The absence of trunk control may increase ACL load and predispose one to an injury, especially with knee angles near full extension.^[81–87] Altered weighting of the trunk may have direct effects on loading of the knee joint. Kulas et al.^[88] recently reported lower-extremity biomechanics during drop landings with added load (10% of bodyweight) to the trunk. The study subjects were divided into either a trunk flexor or trunk extensor landing style. The trunk extensor group increased knee and ankle extensor efforts over 20% and 14–15% during landing, respectively. In contrast, the trunk flexor group did not exceed a 10% increase in either the ankle or knee extensor moments after weighting. The trunk extensor group showed an 11–18% decrease in hip extensor efforts, while flexor group increase 14–19%. These findings are in agreement with Farrokhi et al.,^[89] who reported similar relationships during a lunge manoeuvre. Studies have reported that females demonstrated more erect landings postures^[90–93] and less hip absorption compared with males,^[90] which may be related to the decrease in hip extensor activity reported by Kulas et al.^[88] From these data, it may be concluded that an increase in flexion of the trunk would be an appropriate strategy to reduce ACL injury risk. The resultant increase in hip and knee flexion alone would support this statement. However, the referred studies did not clarify whether or not the behaviour is the same for both sexes. Furthermore, the reported trunk flexion angles do not usually correspond to those angles seen in athletic manoeuvres. Excessive trunk flexion and concomitant hip flexion may influence the gluteus medius and gluteus maximus muscles attachment leading to decreased hip abduction and extension strength. This may in turn result in undesirable joint angles and moments at the knee during dynamic motion, potentially decreasing proximal control.^[94] A recent injury mechanism description in the literature, based on video analysis of basketball players, reported greater hip and knee flexion angles in female players who suffered a valgus collapse with ACL injury compared with males.^[93] The description of the trajectory of the trunk during landing (performance) as well as the sudden reaction movement of the trunk following the perturbation created from the GRF (robustness) may be useful to find sex differences in trunk behaviour and stability.

Neuromuscular control of the trunk is likely different between males and females.^[94] Abdominal activation patterns may differ between sexes during double-leg landings, though they may be reliable for prediction of ACL injuries in females.^[34] Specific local abdominal activation strategies (transversus and internal oblique abdominal muscles) used by males during landing may be safer than general abdominal muscles activation used by females.^[94] Although local activation strategies are beneficial for injury prevention,^[95–98] the general activation of other muscles is also important for core stability. All the torso muscles, acting harmoniously, likely play a critical role in securing spinal stability and reacting against external perturbations.^[99–103] However, further research is needed in this area to know if there are different abdominal patterns between sexes (e.g. muscle patterns that occur in the quadriceps, hamstrings, or gluteus) and how these patterns affect trunk motion and, consequently, knee load.

3.2 Hip Contributions

Increased trunk flexion during landing produced concomitant increases in knee and hip flexion compared with a more erect/extended trunk posture in a drop jump.^[65] An increase in hip flexion could result in reduced shear forces and increased hip extensor effort and energy absorption.^[88,104] The gluteus maximus is an important controller of trunk flexion,^[105–108] and contributes to hip absorption at landing.^[90] Females may land more erect compared with males,^[90,91,93,109] thus decreasing the hip absorption and, consequently, increasing knee and ankle loads.^[90]

Eccentric hip extensor contraction can absorb over 20% of the body's total kinetic energy in females during soft, compared with stiff, landings.^[64] Hence, the trunk and hip flexor/extensor musculatures are an important contributor to loads at the knee, and may influence the GRF from a landing. However, the relative contribution of each joint to energy absorption is poorly understood. Females have lower gluteus maximus activation^[110,111] and hip extension strength compared with males.^[20,112–114] This may indicate the crucial role posterior hip muscles play in preventing knee injuries. However, these data must be taken with caution because these studies did not control the influence of the trunk flexion in gluteus medius activation^[94,115] nor the correlation between strength and electromyography. The potential for increased hip flexion to change the moment arm of the gluteus medius and gluteus maximus could negatively affect neuromuscular control at the hip and in consequence, at the knee.

Hewett et al., in a prospective study conducted with 205 female athletes, observed a greater peak external hip flexion moment during drop landings coupled with a tendency to lower maximum knee flexion angles (10.5° less) in the group that sustained ACL injury compared with the uninjured athletes.^[34] Differences between sagittal plane knee flexion-extension moments and ACL injury status were not reported. However, since the sagittal plane may not be considered a primary predictor of ACL injury in females, it was speculated that the knee and hip joint are better prepared to act as a hinge in this plane. Thus, the musculature that limits sagittal plane trunk, hip and knee motion dissipates sagittal plane knee loads more effectively than coronal plane loads.

Similar to those findings reported by Hewett et al.,^[34] Kernozek et al.^[112] found no significant differences in hip flexion angles, hip extensor moments (internal) and knee moments and angles between males and females also following a drop jump. However, females demonstrated greater vertical and posterior GRF than males. This finding is in agreement with the stiffer landing style in females postulated by Decker et al.^[90] Conversely, Salci et al.^[116] reported decreased hip and knee flexion in female volleyball players during block and spike landings compared with males. Similar results were found by Schmitz et al.^[117] in single-leg drop landings tasks, where females exhibited decreased hip and knee flexion angles compared with males. In contrast, Hewett et al.^[118] did not find differences in hip sagittal plane kinetics and kinematics during single-leg horizontal hops, reinforcing the ‘hinge’ mechanism theory for sagittal plane. Theoretically, decreased hip and knee flexion may increase anterior shear forces and therefore ACL load.^[81–86,119] Decreased hip flexion angles may inhibit hip extensor muscles, increasing quadriceps extensor torques. Greater GRF in combination with greater quadriceps force may increase the anterior translation force to the tibia excessively, especially near full knee extension,^[81,82,84,85,119,120] where the ACL is at higher risk of injury.^[31]

Only a few studies have examined sex differences in the biomechanics of the hip and knee exclusively in the sagittal plane during the cutting manoeuvre. McLean et al.^[120] reported less hip and knee flexion angles in females compared with males in a side-cut manoeuvre with opposition. In contrast, Landry et al.^[121] reported decreased hip flexion angles and smaller hip flexion moments in females compared with males, but no differences in knee flexion angles and moments during unanticipated side-cut manoeuvres.

Yu et al.^[122] and Chappell et al.^[123] reported decreased hip flexion with decreased knee flexion angles in females compared with males during vertical stop jumps. Although Yu et al.,^[122] based on hip and knee angular velocities, suggested that GRF are more related to the motion than to the hip and knee angles, the role of joint positions in the risk of ACL injury has been well established, as joint angles may not only influence GRF but also force vectors of muscles. Controversially, Krosshaug et al.^[93] reported greater hip and knee flexion in female basketball players than males at initial contact and at initial contact during landing tasks. Females demonstrated a 5.3-fold higher relative risk of sustaining a valgus collapse.^[93] This increase in hip flexion has been previously related with greater knee valgus positions in females.^[124,125]

In summary:

- Trunk, arms and head position relative to hip, knee and ankle may influence GRF, energetics and knee load from a landing or cutting manoeuvre.
- The gluteus maximus is an important controller of trunk flexion, and contributes to hip absorption at landing.
- Females may land more erect compared with males, thus decreasing the hip absorption and, consequently, increasing knee and ankle loads.

4. Coronal Plane Evidence: Proximal Control of Knee Stability

4.1 Trunk Contributions

Minimal evidence exists regarding the influence of the trunk on the hip, knee and ankle. The video evidence of ACL injuries reported by Hewett et al.^[125] shows that the female trunk usually moves lateral to the ACL-injured limb as the knee abducts, while this is not a common observation in males (figure 1). A possible close relationship between the position of the trunk and lower limb has been established by Dempsey et al.^[124] The authors recently reported that sidestep cutting techniques influence peak valgus and internal rotation moments in healthy young male athletes (around 21 years old). A foot position away from the midline with the GRF lateral to the knee-joint centre and trunk leaning and rotating to the opposite direction with respect to the cut (displacing the centre of mass away from the plantar surface of the foot) may significantly increase lower-extremity valgus and internal rotation loads at the knee joint during the weight acceptance phase. Moreover, ipsilateral trunk lean may be a sign of weak hip abductors as it moves the centre of mass closer to the stance limb to reduce demand on the weak abductors,^[126] therefore considerably affecting core stability and robustness.

Pollard et al.^[127] speculated that females lean the trunk over the stance limb and agreed with the results of Dempsey et al.^[124] who observed a displaced foot at initial contact among females who presented with greater external knee abduction during side cutting. Knee valgus has been found to be one of the strongest predictors of ACL injury in female athletes.^[34] During single-leg landing and cutting, the entire body mass must be balanced over one lower extremity. Because the trunk, head and arms comprise greater than half of the body's mass, lateral trunk motion increases GRF and knee abduction load. Therefore, technique modification and feedback would be an important element to include in prevention programmes to decrease knee valgus torque in sports involving side-step cutting.^[126]

Zazulak et al.^[128] reported that lateral displacement was a strong predictor of knee ligament injuries. Trunk displacement, proprioception and history of low back pain predicted knee ligament injury with 91% sensitivity and 68% specificity, and specific ACL injuries with 91% accuracy in female athletes. Low back pain may decrease force,^[129–131] hip strength^[132] and endurance,^[133,134] and may alter activation patterns (preactivation and delayed reflex activation),^[135–140] postural control,^[141,142] trunk proprioception,^[143–145] side-to-side weight-bearing symmetry^[146] and gluteal activation.^[147–149] Thus, low back pain may decrease the capability to react against a movement and may reduce trunk equilibrium and robustness. This may unexpectedly move the centre of mass and potentially excessively load the knee joint.

Zazulak et al.^[128] employed open kinetic chain movements to detect proprioceptive deficits at the trunk. Most sport manoeuvres of the lower extremity are performed through closed kinetic chain movements, during which ACL injuries likely occur. Studies incorporating more functional tasks are needed to confirm these findings. However, the role of lateral trunk flexion in ACL injury risk remains controversial. Zeller et al.^[150] reported that female athletes had a decreased amount of lateral trunk flexion in a kinematic study during single-

legged squat compared with their male counterparts. This was related to a greater knee valgus angle presented during the same task in females.

Thus, core stability in the coronal plane may have a profound influence on distal joints. Deficits in neuromuscular control of the trunk during cutting and landing may lead to uncontrolled lateral trunk motion that may increase knee abduction motion and torque through mechanical (lateral GRF motion)^[127,151] and neuromuscular (increased hip adductor torque)^[34] mechanisms, consequently increasing strain on the ACL and leading to injury via either one or both of these mechanisms. Disturbances in trunk motions may increase the ACL injury risk by altering transmission of forces distally and by inducing deleterious joint positions. Core stability may be a crucial component of prevention programmes,^[148] although further research is needed to better understand the exact role of coronal plane trunk biomechanics in the genesis of ACL injuries.

4.2 Hip Contributions

The contributions of the hip musculature to knee abduction have been studied in running, landing, squatting and side-step cutting manoeuvres. Female recreational athletes were found to have greater peak hip adduction angles with greater peak knee abduction angles when running compared with their male counterparts.^[123,152] In contrast, hip moments may not differ between sexes for running actions.^[123] During the landing preparation of a stop-jump task, Chappell et al.^[123] found decreased hip abduction (also decreased hip flexion and hip external rotation) in female compared with male athletes. During the landing task itself, Blackburn and Padua^[65] did not observe coronal plane biomechanical changes at hip and knee joints after increased trunk flexion during landing. A correlation between hip adduction moment and knee abduction moments in ACL-injured subjects ($R = 0.69$) was noted in females who subsequently injured their ACL.^[34] An external hip abduction moment created by the GRF moving lateral to the centre of the femoral head is counterbalanced internally by hip adductor torque. Ford et al.^[153] reported an increase in coronal excursion of the hip and knee after a single drop landing of approximately 13 cm, both medially and laterally, for females compared with males. In contrast, no sex differences for hip abduction at initial contact, maximum hip abduction or maximum hip adduction were reported. These results agree with findings of Pappas et al.,^[154] who found less hip adduction in unilateral (one-legged) compared with bilateral (two-legged) landings despite similar ending position at the time of peak knee flexion. These authors did not observe differences between sexes in hip kinematics during single-legged landings. Significant correlations between coronal plane hip and knee initial contact angles during both types of landings were observed for females but not for males.^[155] Considering all the presented data, hip and trunk excursions and trajectory may be more informative than the final position. Hewett et al. also assessed sex differences on hip kinetics and kinematics in single-legged landings.^[155] The landing task consisted of three consecutive horizontal single-leg hops holding the position after the last one. Females demonstrated greater hip adduction angles at initial contact. The maximal adduction angles and external adduction moments at the hip were significantly greater for the first and second but not for the third hop. Landing sex differences were also reported by Jacobs et al.^[156] during a more complex and functional task that mimics a high-risk posture for ACL injury. The task consisted of a double-legged, broad-jump landing on a single leg.

Females had lower hip abduction compared with males, and moderate correlations were shown between hip abduction strength and knee valgus kinematics for females, but not for males.^[156] In contrast, Padua et al.^[157] examined the relationship between hip strength measured by hand-held dynamometer and joint kinematics during a drop jump task in 63 males and 54 females. The authors reported decreased gluteus medius and gluteus maximus strength that were related to greater knee valgus at initial contact and greater peak knee valgus. Therefore, hip abduction strength assessment may be a potential method to identify those subjects at risk of ACL injury at landing. Also, hip abduction strength programmes may decrease the risk of sustaining an ACL tear at landing. Overall, female soccer players were found to have a significant side-to-side disparity in hip abductor strength not present in males.^[158]

In single-legged squat kinematics, Zeller et al.^[150] reported that female athletes had an increased amount of hip adduction (with concomitant increase in knee valgus) when compared with males. In contrast, Nguyen^[20] only found a trend toward more hip adduction in females, but no statistically significant sex differences were demonstrated in single-legged squat. Most of the data indicate that females have difficulties with hip control and also show the potential importance of gluteus medius strength and activation in order to stabilize the pelvis in single-leg, weight-bearing sport activities.

Studies have reported a significant increase in hip adduction moments in females concomitantly with greater knee valgus moments compared with males during side-step cutting.^[121,159] Sigward and Powers^[160] investigated the hip coronal plane kinematics in a group of females divided by the magnitude of external moment knee valgus during side-step cutting. Contrary to their primary hypothesis, females with excessive knee valgus moment demonstrated significantly larger hip abduction position at initial contact compared with the females with a normal valgus moment. The authors argued that more hip abduction angles may translate the centre of pressure laterally to the centre of mass of the tibia increasing the valgus moment. This may be understood as a dependent task strategy for side stepping to increase the foot width at initial contact, showing that foot positions may influence the kinetics and kinematics of proximal joints.^[126,161] Despite speculating on the impact of the trunk on knee position, the position of the trunk was not analysed in their study.^[160] Coronal plane hip biomechanics are not only affected by the task itself, but also by the situation in which the task is performed. Houck et al.^[161] found that the unanticipated side-step movement was performed with greater hip adduction compared with the anticipated situation. However, the authors included male and female subjects within a single study group, thus, conclusions on sex differences are not possible. Imwalle et al.^[162] investigated the lower-extremity motions in females also assessing the unanticipated cutting manoeuvres with running actions at an angle of 45° or 90°. The authors found that hip adduction was the only significant predictor of knee abduction for both situations.

Hip abduction torque differences between females and males have been observed in some studies,^[49,114,157,163] but not in others.^[113,164] Sex differences in hip abduction torques may explain the higher injury incidence in females. Intervention strategies that target sex differences hip adduction torques (increasing hip abduction strength) may optimize ACL injury prevention programmes, specifically for female athletes.^[148]

It has yet to be definitively determined whether there is a relationship between hip abduction strength and lower-extremity valgus positioning. Proper functioning (strength and recruitment) of the posterior-lateral hip musculature is essential to provide proximal stability for lower-extremity motion during functional activities. Little to no correlation has been found between hip abduction torque^[20,111,163,164] and gluteus medius activation^[108,109] with knee valgus during different tasks. Measurement methods may explain these findings. Hip abductor strength is measured using isokinetic and hand-held dynamometer devices during open chain tasks, which differs from what occurs in athletic manoeuvres. Moreover, these studies did not control the influence of the trunk flexion in gluteus medius activation, which could influence the obtained results. Therefore, neuromuscular control of the hip in the coronal plane is required not only to stabilize the trunk and pelvis, but also the knee joint.

In summary:

- Females and males have significantly different trunk and hip movements in the coronal plane during landing, squatting and side-step tasks. Specifically, females appear to exhibit movement patterns at the trunk that increase knee abduction.
- Studies indicate that abduction at the knee joint predicts risk for ACL injury.
- Deficits in neuromuscular control of the trunk and hip during cutting and landing may lead to uncontrolled lateral trunk motion.
- Targeted neuromuscular training of the trunk and hip to reduce movements that contribute knee abduction may decrease injury risk.

5. Transverse Plane Evidence for Proximal Control of Knee-Joint Stability

5.1 Trunk Contributions

Investigations about the influence of transverse plane movements on the risk of ACL injury are scarce. Dempsey et al.^[124] recently reported that placing the foot away from the midline while the trunk is leaning and rotating to the opposite direction to the cut significantly increased knee abduction and internal rotation loads at the knee in the weight acceptance phase. The rotation of the trunk transfers transverse plane motions to the hip through the pelvis, potentially producing hip adduction and internal rotation that may in turn induce knee abduction. These data coincide with the ‘position of no return’ described by Ireland^[61] to explain a non-contact ACL injury mechanism and where Ireland warned against flexion and rotation to the opposite side of the trunk. In contrast, Blackburn and Padua^[65] found no influence of trunk flexion at the hip and knee position in the transverse plane. No studies examining sex differences in the transverse plane trunk motions were found; therefore, further research is needed in this area.

5.2 Hip Contributions

Transverse plane hip contributions to knee biomechanics have been investigated in running, side-step cutting, and landing manoeuvres. Ferber et al.^[151] reported significantly greater hip internal rotation angles and hip negative work in the transverse plane during running in female recreational athletes compared with males. However, Landry et al.^[121] found that

females produced a greater overall hip external rotation moment than did male subjects during the early stance phase of the unanticipated straight run. Position of the foot at initial contact may explain these contradictory data.

The contribution of the hip musculature during side-step cutting is supported by findings of McLean et al.,^[159] who showed that the peak knee abduction moment was more sensitive to initial hip internal rotation and knee abduction position ($R = 0.76$) in females compared with males. These findings are in agreement with those reported by Sigward and Powers^[160] who found significantly greater hip internal rotation and greater internally rotated foot at initial contact in the excessive valgus moment compared with a normal valgus group during side-step cutting. During the same manoeuvre, Pollard et al.^[149] reported that female athletes demonstrated significantly greater hip internal rotation angles at early deceleration compared with male athletes. In contrast, Landry et al.^[121] reported that female subjects sustained a larger hip external rotation moment than male subjects during the early stance phase of an unanticipated side-cutting manoeuvre. However, the moment magnitudes were much smaller than the maximal moments reached later in midstance phase. It remains unclear if these moment differences at the smaller magnitudes during early stance serve as potential risk factors for ACL injury.

For landing tasks, Lephart et al.^[164] found that females exhibited significantly lower leg internal rotation maximum angular displacement for both single-leg landing and forward hop. Specifically, for the single-leg land, females had significantly greater hip internal rotation maximum angular displacement, and less lower leg internal rotation time to maximum angular displacement compared with males.^[164] For the forward hop, females had significantly greater hip rotation time to maximum angular displacement than males.^[164] Surprisingly, Pollard et al.^[149] reported changes in the hip, but not in the knee, after in-season neuromuscular training. Interestingly, the authors demonstrated how hip internal rotation may be decreased after an adequate neuromuscular training, as they found 6.2° decreases in hip internal rotation and 2.8° greater hip abduction angles during the early deceleration phase of landing following the season, without differences in knee valgus and flexion angles. Although the authors did not assess sex differences in hip contributions to knee-joint motions, these results point out the relevance of prevention programmes to decrease the risk of ACL injury. During vertical stop jump tasks, Chappell et al.^[123] found decreased hip external rotation and increased knee internal rotation angles in females compared with males at landing. In contrast, Nguyen^[20] did not observe significantly greater hip internal excursion in females compared with males during a single-leg squat, although differences in the assessed task may explain differing results. Sex differences in hip or trunk contribution to knee-joint motions are likely task-dependent.

The gluteus maximus and gluteus medius act synergistically to stabilize the pelvis in all planes of motion and control rotation at the hip, especially in single-leg stance. While the gluteus medius is the primary abductor of the hip, the gluteus maximus functions primarily as an extensor and, secondarily, as an external rotator of the hip. Decreased activation of proximal stabilizing muscles may lower load-bearing capacity of the knee joint and predispose it to injury. Zazulak et al.^[108] found decreased gluteus maximus electromyographic activity at landing in female soccer, basketball and volleyball players

compared with males. Gluteal muscles are able to change their functions depending on the hip position.^[91] Therefore, it would be desirable to monitor and provide information about hip and trunk position when considering the activation of these musculatures.

Females demonstrated decreased values in hip external rotation strength compared with males measured with a hand-held dynamometer.^[49,165] In contrast, Claiborne et al.^[111] did not find differences in hip musculature strength measured with isokinetics when normalized to body mass. Weakness or poor neuromuscular control in hip external rotators in females may increase the injury risk of the lower extremity, as reported by Leetun et al.^[49] Core stability was used synonymously with isometric hip strength.^[49]

To affirm this contention, information and interrelation of all components involved in neuromuscular control of the core would be necessary. Lawrence et al.^[165] studied hip external rotation strength on kinematic and kinetic variables during single-leg drop landings in females. The authors stratified the group of females according to 'strong' or 'weak' hip external rotation strength with a hand-held dynamometer. The 'strong' group demonstrated significantly lower peak vertical GRF and external knee flexor moment. The 'weak' group had significantly greater external knee adduction moment, net knee anterior shear joint reaction force and a greater hip external adduction moment. Therefore, this study demonstrated that hip strength may be related to high-risk landing strategies and highlights the importance of the hip external rotators at potentially preventing ACL injuries.^[165] However, caution must be taken when interpreting these results due to the limitations of hand-held dynamometry with open kinetic chain measurements.

In summary:

- The rotation of the trunk transfers transverse plane motions to the hip through the pelvis, potentially producing hip adduction and internal rotation that may in turn induce knee abduction.
- There is minimal evidence examining sex differences in the transverse plane trunk motions.
- Peak knee abduction moment appears to be more sensitive to initial hip internal rotation and knee abduction position in females.
- Weakness or poor neuromuscular control in hip external rotators in females may increase the injury risk of the lower extremity.

6. Conclusions

This review has focused on the contributions of proximal controllers of the trunk and hip- to knee-joint motions. Sex differences in the biomechanics of trunk and hip in sagittal, coronal and transverse planes have been identified and discussed. We have used this approach to better understand the neuromuscular imbalances and the higher incidence of ACL injury observed in female athletes. Considering the increased risk of radiographically diagnosed knee osteoarthritis following ACL injury, regardless of whether the ligament is reconstructed or not, prevention is currently the only effective treatment for this devastating

athletic injury. Based on the presented evidence, the following conclusions can be generated regarding sex-based differences in the proximal control of the knee joint:

- The risk of ACL injury likely results from a combination of disturbances in all three planes of motion.
- Females may land with less trunk and hip flexion compared with males, which results in decreased energy absorption capacity of the musculoskeletal system.
- GRF (normalized) at landing may be higher in females compared with males. Greater reaction forces with the hip and knee flexion angles near extension may overload the ACL and place it at high risk of injury.
- The lateral displacement of the trunk centre of mass away from the knee joint may increase knee valgus and can potentially increase ACL injury risk.
- Females may show greater hip adduction while performing sport manoeuvres (running, landing, squatting and cutting), which may increase knee valgus and hip internal rotation and place the ACL at increased risk of rupture.
- Hip strength training may decrease the risk of ACL injury by modifying high-risk positions about the knee.
- The influence of transverse plane trunk biomechanics on the knee joint needs to be further studied, as little evidence has been reported in the literature.
- Significantly greater hip internal rotation has been reported among females compared with males during running, side-step cutting and landing, and is related to knee abduction in female athletes.
- Proximal control of the knee joint is sex and task dependent.
- Prevention programmes targeted towards trunk and hip neuromuscular control may help decrease the risk of ACL injuries in athletes, especially female athletes.

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Fig. 1. Photograph of an athlete sustaining an anterior cruciate ligament injury event, which illustrates a common mechanism of injury in female athletes, with trunk movement lateral to and away from the body's midline as the knee collapses toward the midline.