A review of recent perspectives on biomechanical risk factors associated with anterior cruciate ligament injury.

Abstract

There is considerable evidence to support a number of biomechanical risk factors associated with non-contact anterior cruciate ligament (ACL) injury. This paper aimed to review these biomechanical risk factors and highlight future directions relating to them. Current perspectives investigating trunk position and relationships between strength, muscle activity and biomechanics during landing/cutting highlight the importance of increasing hamstring muscle force during dynamic movements through altering strength, muscle activity, muscle length and contraction velocity. In particular, increased trunk flexion during landing/cutting and greater hamstring strength are likely to increase hamstring muscle force during landing and cutting which have been associated with reduced ACL injury risk. Decision making has also been shown to influence landing biomechanics and should be considered when designing tasks to assess landing/cutting biomechanics. Coaches should therefore promote hamstring strength training and active trunk flexion during landing and cutting in an attempt to reduce ACL injury risk.

Keywords: strength, landing, trunk, knee.

Introduction

Anterior cruciate ligament (ACL) injury is a common debilitating sports injury which often results in reduced knee function through the development of knee instability and subsequent damage to the menisci and articular surfaces (Irvine & Glasgow, 1992; Smith, Livesay, & Woo, 1988). Approximately 70% of ACL injuries have been reported to occur during non-contact situations, such as landing, deceleration and rapid change of direction (Griffin et al., 2000). Females have been shown to be 6 to 8 times more likely to sustain an ACL injury compared to males competing in the same sport (Arendt & Dick, 1995). A number of biomechanical risk factors have been associated with this gender difference. Previous reviews have discussed gender differences in kinematics and kinetics during landing or cutting manoeuvres (as summarised in the first two sections of this review). However, more recent perspectives, such as investigation of the role of the trunk, the effects of decision making and the relationships between muscle strength, activity and landing/cutting biomechanics, have received little consideration in previous reviews. The purpose of this paper is to review the current evidence related to biomechanical risk factors associated with the gender difference in the incidence of ACL injury and highlight current perspectives relating to these biomechanical risk factors which require further investigation.

Gender differences in landing and cutting kinematics

A number of studies which have investigated the sagittal plane kinematics of landing and/or cutting manoeuvres report that females tend to contact the ground with the hips and knees more extended than males (Decker, Torry, Wyland, Sterett, &

Steadman, 2003; James, Sizer, Starch, Lockhart, & Slauterbeck, 2004; Malinzak, Colby, Kirkendall, Yu & Garrett, 2001; Yu, Lin, & Garett, 2006). Contraction of the quadriceps, acting through the patellar tendon, produces an anteriorly directed shear force to the proximal tibia. For a given load acting through the patellar tendon, the less knee flexion, the greater the strain on the ACL is likely to be due to the inverse relationship between knee flexion and the patella tendon-tibia shaft angle (angle between the long axis of the tibia and the line of action of the patellar tendon in the sagittal plane) (Li et al., 1999; Nunley, Wright, Renner, Yu, & Garett, 2003). Furthermore, as knee flexion angle decreases, hamstring tendon-tibia shaft angle has been shown to decrease to the point where hamstring muscle force may increase the anterior shear force acting at the proximal tibia when the knee is close to full extension (Lin et al., 2012). Non-contact ACL injury has been reported to occur frequently when the knee is close to full extension (Boden, Dean, Feagin, & Garett, 2000; Olsen, Mykelbust, Engebretsen, & Bahr, 2004). Consequently, reduced knee flexion at initial ground contact in females may increase the risk of ACL injury relative to males.

Studies which have investigated the frontal plane kinematics of landing/cutting report females to exhibit greater maximum knee valgus angle and greater range of motion of knee valgus when landing compared to males (Ford, Myer, & Hewett, 2003; Hughes, Watkins, & Owen, 2008; Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Malinzak et al., 2001). Due to the structure of the knee, angular motion about an anteriorposterior axis (knee valgus/varus) is very limited, whereby the hamstring muscles tend to stabilise the knee the frontal plane (Lloyd & Buchanan, 2001). Boden et al. (2000) and Olsen et al. (2004) reported that non-contact ACL injury frequently occurs when the knee exhibits a valgus movement. Consequently, the greater maximum knee valgus angle and range of motion of knee valgus reported in females during landing/cutting may increase the risk of ACL injury relative to males. Finally, Pollard, Sigward, & Powers (2010) reported that female subjects who exhibited low peak flexion angles (combined knee and hip flexion) during landing displayed significantly greater peak knee valgus angles. This suggests there may be an association between frontal and sagittal plane kinematics at the knee during landing which combine to increase ACL injury risk in females.

Gender differences in landing and cutting kinetics

During landing, lower limb joint movements are determined by the resultant joint moments acting about the joints. Studies examining internal joint moments (moment produced about a joint by the internal structures within and crossing a joint) of the lower limbs during landing indicate that females tend to exhibit reduced hip extension moment and greater knee extension moment (Chappell, Yu, Kirkendall, & Garett, 2002; Salci, Kentel, Heycan, Akin, & Korkusus, 2004; Yu et al., 2006) than males, even when accounting for differences in body size. In the frontal plane, studies examining the external joint moments (moment acting about a joint due to external forces which must be resisted by an opposing moment produced by the internal structures within and crossing a joint) report that females tend to exhibit greater knee valgus moments during landing/cutting compared to males (Chappell et al., 2002; Earl, Monteiro, & Snyder, 2007; Kernozek, et al., 2005; McLean, Huang, & van den Bogert, 2005; McLean, Walker, & van den Bogert, 2005; Pappas, Hagins, Sheikhzadeh, Nordin, & Rose, 2007). Knee valgus moments have been shown to cause high loading of the ACL (Markolf et al., 1995; Mizuno, Andrish, van den Bogert, & McLean, 2009).

The internal moment about a particular axis through a joint is the predominantly determined by the moment due to the various muscles which, in turn, depends on both the muscle forces and the moment arms of the muscles. Figure 1 shows the forces acting on the proximal end of the tibia due to the ACL, posterior cruciate ligament (PCL), quadriceps and hamstrings and their moment arms in the sagittal plane when the knee is close to full extension, i.e., when non-contact ACL injury is most common.

Figure 1 about here.

Kellis and Baltzopoulos (1999) calculated the moment arms of the patella tendon and the hamstrings for ten male subjects in the sagittal plane during submaximal knee flexion-extension movement at very slow (non constant) angular velocity using videofluoroscopy. Moment arms were taken as the perpendicular distance between the muscle tendon and the central contact point of the tibiofemoral joint. Between 0-10^{o} of knee flexion, the mean moment arm of the patella tendon was found to be 36.9 ± 3.2 mm and the mean moment arm of the hamstrings was found to be 23.9 ± 2.6 mm. Other studies report values ranging from 30 mm to 40 mm for the moment arm of the patella tendon (Grood, Suntay, & Noyes, 1984; Herzog & Read, 1993; Smidt, 1973) and ranges from 20 mm to 41.3 mm for the moment arm of the hamstrings

(Herzog & Read, 1993; Smidt, 1973; Wretenburg, Nemeth, Lamontagne, & Lundin, 1996). These data suggests that the mechanical advantage of the quadriceps may be greater than that of the hamstrings. When the knee is in a flexed position (between 15^o and 60^o of knee flexion), since the hamstrings work with the ACL to prevent anterior dislocation of the proximal tibia relative to the distal femur (Li et al., 1999), this reduced mechanical advantage of the hamstrings relative to the quadriceps may increase the risk of overloading the hamstring muscles, which in turn may cause increased anterior shear force on the proximal end of the tibia which may strain the ACL. However, at low knee flexion angles (less than 15^o), co-contraction of the hamstrings has been shown to not significantly reduce tibia anterior translation (Li et al., 1999).

Figure 2 shows the forces acting on the proximal end of the tibia due to the ACL, PCL, semimembranosus, semitendinosus, gracilis and biceps femoris and their moment arms in the frontal plane when the knee is close to full extension, i.e., when non-contact ACL injury is most common.

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Figure 2 about here.

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Wretenburg et al., (1996) calculated the moment arms of the semimembranosus, semitendinosus, gracilis and biceps femoris in the frontal plane for ten male and seven female subjects using MRI measurements. Moment arms were taken as the perpendicular distance between the muscle tendon and the central contact point of the tibiofemoral joint and were measured with no muscle contraction. The absolute moment arms of the semimembranosus, semitendinosus, gracilis and biceps femoris in the frontal plane were significantly greater in males than females. Even when normalised to height, the moment arms of all muscles were still greater in males than females. These data suggests that the mechanical advantage of the semimembranosus, semitendinosus, gracilis and biceps femoris in the frontal plane may be greater in males than females. Since these muscles work with the passive support structures of the knee to prevent abnormal movement of the knee joint in the frontal plane (Lloyd & Buchanan, 2001), this reduced mechanical advantage in females compared to males may increase the risk of overloading the semimembranosus, semitendinosus, gracilis and biceps femoris, which in turn may increase the likelihood of an abnormal movement of the knee joint in the frontal plane which may strain the passive support structures of the knee.

In summary, ACL injury is likely to occur due to abnormal movement of the tibiofemoral joint. In the sagittal plane, an imbalance of quadriceps muscle force over hamstring muscle force resulting in anterior shear force acting on the proximal end of the tibia is likely to cause an abnormal movement of the tibiofemoral joint (anterior displacement of the tibia relative to the femur) which will increase ACL strain. The greater knee extension moment in females compared to males suggests females' quadriceps muscles produce greater force relative to the force due to the hamstrings than males. Therefore future research should focus on ways to increase knee flexion angle and reduce knee extension and valgus moments in females through increasing hamstring muscle forces, in particular those muscles which attach to the medial aspect of the tibia. Recent perspectives on examining biomechanical risk factors associated with ACL injury have focussed on investigation of the role of the trunk, the effects of decision making and the relationships between muscle strength, activity and landing/cutting biomechanics. Whilst many of the studies focussing on these recent perspectives have identified relationships between these independent variables and biomechanical variables that have previously been identified as being associated with the gender difference in ACL injury incidence (as described previously), limited direct investigation into gender effects has been conducted. Therefore it is proposed that future research should be conducted in these areas to clearly identify if gender differences exist within these new perspectives.

The effects of trunk position and load on landing/cutting biomechanics

Through analysis of videos in which ACL injury occurred, Hewett, Torg and Boden (2009) identified that non-contact ACL injury was associated with reduced forward trunk lean and greater trunk lateral flexion, where the body was shifted towards the landing leg at the time of injury. This is also supported by Boden et al., (2000) who found that at the time of ACL injury the trunk tended to be upright and/or laterally flexed. Zazulak, Hewett, Reeves, Goldberg and Cholewicki (2007) prospectively examined the relationship between trunk control and ACL injury by measuring trunk displacement after the release of a sudden force in a group of 277 collegiate athletes. Of the athletes measured, 25 sustained a knee injury and 6 sustained ACL injury (4 females and 2 males). Trunk displacements at 150 ms following release of the force and maximum trunk displacement were significantly greater in the knee injured, ligament injured and ACL injured groups compared to the non injured athletes. Of the variables analysed, lateral displacement of the trunk was the strongest predictor of ligament injury.

Trunk flexion is likely to influence lower extremity biomechanics through altering hip extensor and knee flexor muscle function (Grasso, Zago, & Lacquaniti, 2000; Lieberman, Raichlen, Pontzer, Bramble, & Cutright-Smith, 2006; Paul, Salle, & Frings-Dresen, 1996) and altering the moment due to the trunk about the lower extremity joints (Blackburn & Padua, 2009). Flexion of the trunk is often accompanied by anterior pelvic tilt. Anterior pelvic tilt will lengthen the gluteus maximus muscle and the hamstring muscle group, influencing the force-length relationship of the these muscles, whereby these muscles are positioned in such a way as to increase their ability to exert force (Kulas, Hortobagyi, & Devita, 2010). Therefore, increased trunk flexion during landing/cutting is likely to result in increased length of the hamstrings and gluteus maximus than when landing with less trunk flexion which, in turn, will increase muscle forces. This increased force production of the gluteus maximus and the hamstrings may result in increased hip extension moment, reduced knee extension moment and reduced knee valgus moment during landing, all of which have been proposed to be associated with reduced ACL loading (Chappell et al., 2002; Salci et al., 2004; Yu et al., 2006).

Trunk flexion is likely to influence the moment due to the trunk about the hip and knee in the sagittal plane. This occurs due to the centre of mass of the trunk moving forward with increased trunk flexion, causing the centre of mass of the trunk to move closer to the knee and further away from the hip in the horizontal plane. Since the moment due to the trunk will be the product of the weight of the trunk and the horizontal distance between the centre of mass of the trunk and the joint centre (i.e. the moment arm of the trunk), increased trunk flexion is likely to increase the moment due to the trunk about the hip but decrease the moment due to the trunk about the knee (Blackburn & Padua, 2009).

Due to these factors, recent research examining lower extremity biomechanical risk factors associated with ACL injury has therefore focused on the influence of trunk load and trunk motion (Blackburn & Padua, 2009; Chaudhari, Hearn, & Andriacchi, 2005; Dempsey, Elliott, Munro, Steele, & Lloyd, 2012; Janssen, Sheppard, Dingley, Chapman, & Spratford, 2012; Kulas, et al., 2010; Kulas, Zalewski, Hortobagyi, & Devita, 2008; Nagano, Ida, Akai, & Fukubayashi, 2011; Shimokochi, Ambegaonkar, Meyer, Lee, & Shultz, 2013). A summary of the reported effects of trunk flexion and trunk loading on lower extremity biomechanics during landing/cutting manoeuvres is shown in Table 1.

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Table 1 about here.

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The findings of these studies provide strong evidence that trunk loading and trunk position alters the lower extremity biomechanical risk factors associated with ACL injury. In particular, increased trunk load and reduced trunk flexion have been shown to be associated with increased knee anterior shear force during two-footed landing (Kulas et al., 2010) and increased ACL forces during single-leg squats (Kulas, Hortobagyi, & DeVita, 2012). Initial findings examining relationships between frontal and transverse plane motion of the trunk with frontal plane loading of the knee when in single limb stance show some association between these variables. Chaudhari et al. (2005) report that preventing weight from moving over the plant leg through constraining arm movement may increase knee valgus loading in cutting whereas Dempsey et al. (2012) report a significant positive correlation between trunk lateral flexion towards landing leg and knee valgus moment during single leg landing. Furthermore, Frank et al. (2013) reported increased knee varus moments were associated with limited trunk rotation away from the stance limb and towards the direction of travel during a cutting task. Therefore, further investigation is required to verify the relationship between trunk movement and knee loading in the frontal and transverse planes during different tasks in which ACL injuries frequently occur and further investigation is required to determine whether gender differences exist in trunk position during landing and cutting which may contribute to the gender difference in ACL injury incidence.

The relationships between muscle activity, strength and landing/cutting biomechanics

During landing and cutting, while the quadriceps muscles contract to attempt to control knee flexion through eccentric contraction, co-contraction of the hamstrings is essential to prevent excessive ACL loading due to the anterior shear force produced by the quadriceps. Due to their attachments on the lateral and medial aspects of the tibia, the hamstring muscles also help control transverse and frontal plane motions of the knee (Lloyd & Buchanan, 2001). For example, Louie and Mote (1987) found that co-contraction of the muscles surrounding the knee increased torsional stiffness of the knee joint and Olmstead, Weavers, Bryant, and Gouw (1986) found that contraction of the hamstrings to produce a relatively small flexion torque at the knee (less than 20% maximum torque) increased valgus stability of the knee. A combination of anterior shear force acting on the proximal tibia and valgus loading result in loading of the ACL exceeds the loading due to each of these factors independently (Berns, Hull, & Patterson, 1992; Markolf et al., 1995) which further highlights the important role of the hamstring muscle group in the prevention of non contact ACL injury. A number of studies have reported females to posses lower strength of the hamstrings compared to males, even when normalised to body weight (Hakkinen, Kraemer, & Newton, 1997; Huston & Wojtys, 1996; Salci et al., 2004). Furthermore, lower hamstring to quadriceps strength ratio's have been observed in females compared to males and have been reported to be due to reduced hamstring strength in females rather than due to differences in quadriceps strength (Myer et al., 2009). Lower hamstring to quadriceps strength ratio's have been reported to be associated with greater frontal and transverse plane motion during dynamic activities (Hewett et al., 2005). Since muscle strength is modifiable, Hewett et al. (1996) investigated the effect of a plyometric training intervention on landing mechanics and lower limb strength. The results showed plyometric training significantly increased hamstring strength which was also associated with significant reductions in frontal plane knee loading during a landing task. However, recent reviews of the effects of training programs on ACL injury (Dai, Herman, Lui, Garrett, & Yu, 2012; Donnelly et al., 2012) highlight that whilst many training programs result in altered lower extremity movement patters, the effect of these training programs on ACL injury incidence is inconsistent and the mechanisms by which biomechanical risk factors are influenced by training is unclear. Furthermore, a systematic review by Stojanovic and Ostojic (2012) examining nine studies which investigated the effects of training on ACL injury concluded that multicomponent training programs which included balance, plyometrics, agility and strength components appeared to be the most effective. However, more research is required to further verify the effects of training programs on ACL injury incidence in both males and females.

The force a muscle produces during a landing or cutting manoeuvre depends on a number of factors; including muscle length, contraction velocity, muscle strength (maximal force output) and muscle activity (number of active motor units and their firing rate). Previous research indicates gender differences exist in muscle activity during landing/cutting, whereby females tend to exhibit greater quadriceps muscle activity and less hamstring muscle activity compared to males (Malinzak et al., 2001) which is likely to result in increase ACL loading. Recent research has attempted to explore the relationships between strength, muscle activity and landing biomechanics. For example, Wild et al. (2013) examined lower limb kinematics of the hip, knee and ankle, ACL forces and muscle activity of six lower limb muscles (Medial Gastrocnemius, Tibialis Anterior, Vastus Medialis, Rectus Femoris, Semitendinosis and Biceps Femoris) during a single-leg horizontal landing in high ($n = 11$) and low ($n = 11$) concentric hamstring strength groups of pubescent females. The results showed that the low hamstring strength group displayed significantly greater knee valgus angles at the time of maximum vertical and anterioposterior ground reaction forces (GRF), significantly less hip abduction moments at the time of maximum vertical GRF and significantly greater ACL force at the time of maximum anterioposterior GRF compared to the high hamstring strength group. No significant differences were observed in the time of onset of muscle activity and the time to peak amplitude between high and low strength groups. These results suggest that those with low hamstring strength display a reduced ability to control frontal plane alignment of the lower limb during landing despite similar timing of muscle activity. Therefore, for the muscles that control the stability and movement of the knee, differences in peak strength may have a greater influence on the prevention of excessive frontal plane motion and ACL force than differences in the timing of muscle activity, however further investigation is needed to examine the magnitude of muscle activity to further investigate these relationships.

Since reduced hip extension moment and increased knee extension moment have been associated with the gender difference in the incidence of ACL injury, Stearns et al. (2013) examined the relationship between hip and knee extension isometric strength and extension moments of the hip and knee observed during a two-footed drop-jump task in 20 male and 20 female recreational athletes. The results showed females displayed a significantly greater knee to hip extension moment ratio during landing and a significantly greater knee to hip extension isometric strength ratio compared to males. The results also showed that there was a significant positive relationship between landing knee to hip extension moment ratio during landing and knee to hip isometric strength ratio. These findings suggest that gender differences in hip and knee extensor moments observed during landing may partly be explained by differences in strength and therefore strengthening of the muscles that control hip extension (Hamstrings and Gluteus Maximus) in females may be important to reduce the gender difference in the incidence on non-contact ACL injury.

The hip external rotators and abductors help prevent excessive valgus knee motion during landing through eccentric control of the femur. Weakness and/or insufficient activation of these muscles in females may also contribute to the greater incidence of non-contact ACL injury in females. Some studies have found an association between reduced hip abduction and external rotation strength and increased knee valgus motion during landing (Jacobs, Uhl, Mattacola, Shapiro, & Rayens, 2007; Wallace et al., 2008), however other studies have contradicted these findings (Bolgla, Malone, Umberger, & Uhl, 2008; Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008; Patrek, Kernozek, Willson, Wright, & Doberstein, 2011). The reason for the discrepancy between these studies may, in part, be due to a lack of association between the muscle force produced during a dynamic task and strength during isometric or isokinetic tests, since other factors will also influence muscle force during a dynamic task. Therefore, Homan et al. (2013) measured hip external rotation and abduction isometric strength and examined relationships between these factors and gluteal muscle activity, frontal plane angles of the hip and knee and transverse plane motion of the hip during a two legged drop jump landing. For hip abduction strength, no significant differences were observed in landing kinematics of the hip and knee between high and low strength groups, however, the high hip abduction strength group displayed significantly less gluteus medius EMG amplitude compared to the low strength group. For hip external rotation strength, the high strength group exhibited significantly less external rotation, valgus knee angles and gluteus maximum muscle activity than the low strength group. These results therefore suggest that individuals with reduced hip abduction strength may compensate for strength deficiencies through increased activation the hip abductors in an attempt to maintain frontal plane alignment during landing.

Overall, studies examining the relationships between lower limb strength, muscle activity and landing/cutting biomechanics suggest that strengthening the hamstring muscles can be important in preventing ACL injury through enhanced ability to control frontal plane motion and loading of the knee and reducing the net knee extension moment during landing/cutting. There is less evidence to support the relationship between hip abduction and external rotation strength in controlling knee motion and loading, suggesting that the activity of these muscles may be more important in controlling frontal plane motion of the knee, however further research is required to confirm these findings.

The effects of decision making on landing/cutting biomechanics

Initial research examining gender differences in landing and cutting biomechanics have used highly standardised tasks which are predictable and controlled, such as drop-landings and drop-jumps from a set height (Decker et al. 2003; Kernozek et al., 2005; Salci et al., 2004) or cutting at a pre-determined angle (James et al., 2004; Malinzak et al., 2001). Whilst these standardised tasks have allowed us a greater understanding of biomechanical risk factors associated with ACL injury through controlling a number of potentially confounding factors, minor variations in jump landing tasks have been show to significantly affect landing biomechanics (Cruz et al., 2013). These tasks do not reflect the random nature of sports where participants are often required to respond to a number of different stimuli simultaneously and have to make adjustments during landing/cutting activity in response to these stimuli. This has led to recent research examining landing biomechanics during anticipated and unanticipated tasks to investigate the effects of decision making on landing biomechanics (Brown, Palmieri-Smith, & McLean, 2009; Houck, Duncan, & De Haven, 2006; Mache, Hoffman, Hannigan, Golden, & Pavol, 2013; McLean, Borotikar, & Lucey, 2010). For example, Houck et al., (2006) compared trunk orientation in the frontal plane (trunk position relative to the global vertical position), trunk lateral flexion (trunk position relative to the pelvis segment), lateral foot placement, frontal plane hip angle along with hip and knee moments in the frontal plane during anticipated and unanticipated straight line walking and side cutting (approximately 50^{o} change of direction) tasks. The results showed that frontal plane trunk orientation was significantly greater and hip abduction was significantly lower during the unanticipated side-step task compared to all other tasks whereas trunk lateral flexion was relatively similar across all tasks. Frontal plane knee moments were also affected by the decision making, whereby close to initial ground contact, moments were in the valgus direction during unanticipated side-cutting compared to the moments being in the varus direction for all other tasks and knee valgus moments were lower during 10-30% of stance for unanticipated side-cutting task compared to when the side cut was anticipated. These findings suggest that frontal plane hip and knee biomechanics are affected by anticipation and that global trunk orientation is affected by altered lower limb positioning rather than by trunk lateral flexion during unanticipated cutting. However, the speed of the walking and cutting activities were fairly low (means of between 2.2 m/s and 1.9 m/s). Since ACL injury is likely to occur during more dynamic activities it limits the validity of the findings of this study and more research needs to be done in activities more representative of tasks in which ACL injury is common. Also, as with Mache et al., (2013), all unanticipated task were completed after the anticipated tasks. The non-randomised order of the pre-planned and decision making conditions suggest that learning and fatigue effects may have occurred, limiting the strength of any conclusions made.

Decision making has also been found to influence knee valgus moment by McLean et al., (2010) who found the knee valgus moment measured during unanticipated single leg landings (stimulus for which leg to land on given approximately 650 ms before ground contact) was significantly greater than during anticipated single leg landings (stimulus for which leg to land on given approximately 5 s before ground contact). In addition, significant correlations were observed between the peak knee valgus moment measured during anticipated landings and pre-motor times (time between a light stimulus and muscle activation in response) measured during a choice reaction task (subjects were required to move either left or right from a standing position in response to a light stimulus) for both medial gastrocnemius and medial hamstrings. For both muscles, increased pre-motor times were associated with increased knee abduction moment during the push off phase of the landing. The findings of this study further strengthen the link between anticipation and knee valgus moments and highlight a potentially important link between the function of the medial muscles of the lower limb, in particular the medial hamstrings, during a reaction task and valgus moment at the knee during landing.

Since initial research suggests that decision making influences landing biomechanics, Brown et al. (2009) investigated the effects of altering the time prior to landing of an unanticipated stimulus. Thirteen male and thirteen female recreational athletes completed a task involving a 2 m forward jump which subjects were then required to land from in single limb stance and immediately perform a vigorous cut to the opposite side to the leg which they had landed on. The landing leg were given to the subjects in an anticipated condition (5 s prior to the task) and during three unanticipated conditions (approximately 600 ms, 500 ms and 400 ms prior to landing), provided by a light stimulus in a randomised order. For task effects, the results showed that at initial ground contact, subjects displayed significantly greater hip abduction and less hip flexion in unanticipated conditions compared to the anticipated conditions but there was no significant difference between the three unanticipated conditions. Also, peak hip and knee external rotation moments during the first 50% of the stance phase were significantly greater for two of the unanticipated conditions (500 ms and 400 ms) compared to the unanticipated condition. These results suggest that whilst the unanticipated nature of tasks affects landing biomechanics, the timing of the unanticipated stimulus did not show any effect on the biomechanics of landing within the time frames examined in this study. Further investigation is needed into shorted pre-landing stimulus times to further verify these findings.

These studies provide clear indication that decision making does influence the biomechanics of landing/cutting, therefore future research should investigate tasks involving an element of decision making to reflect game situations. Further investigation is required to confirm any differences between males and females in responses to decision making during landing/cutting since many of the findings from the studies involve complex interactions between multiple independent variables such as decision making, gender and type of task. At times, this makes interpretation of the results difficult but highlights the multifactoral nature of biomechanical risk factors associated with ACL injury.

Conclusion

There is general consensus that the biomechanical risk factors associated with the gender difference in ACL injury incidence include less knee flexion at ground contact, greater knee valgus motion, greater knee extension moment and greater knee valgus moment in females than males during landing and cutting manoeuvres. Increasing hamstring muscle force through altering strength, muscle activity, muscle length and contraction velocity is likely to reduce these biomechanical risk factors. Recent research has focussed on the influence of trunk motion and loading along with the relationships between strength, muscle activity and landing/cutting biomechanics. This research has shown that increased trunk flexion and greater hamstring strength are associated with reduced ACL injury risk. Decision making has also been shown to influence landing biomechanics and should be considered when designing tasks to assess landing/cutting biomechanics. Coaches should therefore concentrate on strength training of the hamstrings and encouraging athletes to actively flex the trunk through incorporating training activities which involve decision making during landing and cutting movements in an attempt to reduce ACL injury risk.

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Figure Captions

Figure 1. The forces acting on the proximal end of the tibia due to the quadriceps and hamstrings and their moment arms in the sagittal plane. F_Q = force exerted by the quadriceps, F_H = force exerted by the hamstrings, d_Q = moment arm of the quadriceps (patella tendon), d_H = moment arm of the hamstrings, *ACL* = force exerted by the ACL and *PCL* = force exerted by the PCL.

Figure 2. Anterior aspect of the proximal end of the left tibia and the forces acting on the proximal end of the tibia due to the semimembranosus, semitendinosus, gracilis and biceps femoris and their moment arms in the frontal plane. F_{SM} = force exerted by the semimembranosus, F_{ST} = force exerted by the semitendinosus, F_{GR} = force exerted by the gracilis, F_{BF} = force exerted by the biceps femoris, d_{SM} = moment arm of the semimembranosus, d_{ST} = moment arm of the semitendinosus, d_{GR} = moment arm of the gracilis, d_{BF} = moment arm of the biceps femoris, *ACL* = force exerted by the ACL and *PCL* = force exerted by the PCL.

Tables

Table 1. Summary of studies examining the effects of trunk position and load on lower extremity biomechanics.

Study	Task	Independent variables	Key findings
Chaudhari et al. (2005)	90^{o} cutting	Arm position (no constraint, holding ball in each arm, holding lacrosse stick)	Constraining plant side arm movement increased knee valgus moment
Jansen et al. (2012)	Two footed volleyball block jump landing	Load (9.89 kg weighted vest)	Hip flexion increased at initial contact when unloaded compared to loaded
Kulas et al. (2010)	45 cm two footed drop landing	Load (10% BW weighted vest) and trunk adaptation to load (extensors or flexors)	Added load increased KASF in trunk extensors and increased quadriceps and gastrocnemius forces in both groups. Hamstring force greater in trunk flexor group than extensor group when loaded
Kulas et al. (2008)	45 cm two footed drop landing	Load (10% BW weighted vest) and trunk adaptation to load (extensors or flexors)	Added trunk load and trunk position interactively affect hip biomechanics. Added trunk load increase the biomechanical demand on the knee and ankle regardless of trunk position
Blackburn et al. (2009)	60 cm two footed drop landing	Trunk position (preferred, active flexion)	Active trunk flexion reduced vGRF and pGRF and quadriceps muscle activity
Kulas et al. (2012)	Single leg squat	Trunk position (minimise forward lean, increased forward lean)	Peak ACL forces reduced when moderately increasing forward lean
Shimokochi et al. (2013)	Single leg drop (30 cm for females and 45 cm for males)	Trunk position (self-selected, forward lean, upright)	When compared to forward leaning landing, upright landing showed greater peak vGRF and peak knee extension moment, but less plantar flexion, hip extension moment and muscle activity of the MG, LG and LQ
Dempsey et al. (2012)	Single leg landing following a ball catch	Movement of ball (ball moved towards or away from support leg both early and late)	Movement of ball towards support leg resulted in increased knee valgus moment when compared to ball moving away. Significant positive correlation between trunk lateral flexion towards landing leg and knee valgus moment
Nagano et al. (2011)	180^{o} cutting	Gender	Trunk forward and lateral inclination significantly greater in males than females. Strong positive correlation between trunk forward inclination and knee flexion
Frank et al. (2013)	60^{o} cutting	Trunk motion	Greater knee varus moment associated with reduced trunk rotation away from stance limb (towards direction of travel).

BW = body weight, KASF = knee anterior shear force, vGRF = vertical ground reaction force, pGRF = posterior ground reaction force, MG = medial gastrocnemius, LG = lateral gastrocnemius, LQ = lateral quadriceps.