2006

A Risk Factor Model for Anterior Cruciate Ligament Injury

Gerwyn Hughes
University of San Francisco, ghughes@usfca.edu

J. Watkins

Recommended Citation

Hughes, G. & Watkins, J. (2006). A risk factor model for anterior cruciate ligament injury. Sports Medicine. 36(5): Pp. 411-428.

A risk factor model for anterior cruciate ligament injury.

G. Hughes and J. Watkins.

Department of Sports Science, University of Wales Swansea.

Acknowledgements.

No author has received any financial benefit for the research in this study. We have no potential conflicts of interest relevant to the contents of this manuscript.

Name and address for correspondence.

Name: Gerwyn Hughes.

Address: Department of Sports Science,

University of Wales Swansea,

Singleton Park,

Swansea,

Wales,

SA2 8PP.

e-mail: 189895@swan.ac.uk

Telephone: +44 1792295086

Fax: +44 1792513171

Figure legends.

Figure 1. a) Anterior aspect of the right knee in flexion, b) Normal orientation of the cruciate ligaments in the partially flexed knee.

Figure 2. Free body diagram of forces acting on the proximal tibia in the sagittal plane. Forces due to the Hamstrings (H), Quadriceps (Q), Anterior cruciate ligament (A) and Posterior cruciate ligament (P).

Figure 3. a) Normal orientation of the cruciate ligaments in the partially flexed knee; b) ACL tear due to posterior dislocation of the femur on the tibia; c) PCL tear due to

Figure 4. Model of ACL injury based on passive and dynamic stability of the tibiofemoral joint.

Figure 5. Factors affecting passive stability of the tibiofemoral joint.

Figure 6. Q angle and valgus angle of the right leg.

Figure 7. Intercondylar notch width (A) and notch width index (A/B).

Figure 8. Factors that affect dynamic stability of the tibiofemoral joint.

Figure 9. Effects of knee flexion angle (a) on patella tendon tibia shaft angle (b).

Figure 10. Forces exerted by the quadriceps and hamstrings on the tibia. a) relationship of the hamstrings (H), quadriceps (Q) and patellar ligament (P) to the anterior cruciate ligament (A). b) components of H and P in relation to A: if P_H is greater than H_H, the ACL will be put under strain.

Figure 11. Proposed risk factor mode of ACL injury based on passive and dynamic stability of the tibiofemoral joint.

A risk factor model for anterior cruciate ligament injury.

Contents.

Abstract.

The stability of the tibiofemoral joint is maintained by passive (non-contractile) and dynamic (contractile) mechanisms. The passive mechanisms include the shape of the articular surfaces, the menisci, the ligaments and the joint capsule. The dynamic mechanisms consist of the muscle-tendon units that cross the joint, in particular, the quadriceps and hamstrings. The incidence of non-contact anterior cruciate ligament (ACL) injury is reported to be 6 to 8 times greater in females than males competing in the same activities. A number of intrinsic and extrinsic risk factors have been proposed to account for this gender difference in the incidence of ACL injuries. However, most of the proposed risk factors have arisen from uni-variate correlation studies based on relatively small samples. The purpose of this paper is to present a risk factor model for ACL injury based on a review of passive and dynamic stability mechanisms.

1. ACL injuries.

Anterior Cruciate ligament (ACL) injuries are common and approximately 70% of these injuries occurring in sport [1-3]. ACL reconstruction was the 6th most common orthopaedic procedure performed in the US in 1999 and 2000 with approximately 100,000 being performed annually at a cost of over $2 billion [4-6].

Up to two thirds of patients who have complete ACL tears develop knee instability and, subsequently, damage to the menisci and articular surfaces which significantly affects knee function and leads to a decrease in level of activity [3, 7-9]. Noyes et al. [10] found that in a group of individuals with rupture of the ACL, 31% of patients reported overall difficulty in walking, 44% had difficulties with activities of daily living and 77% had difficulties with playing sport as a direct result of their ACL injury.

Between 70% and 90% of ACL injuries have been reported to occur in non-contact situations [5, 11, 12]. A non-contact situation is where there is no direct contact with the knee when the injury occurs. Most ACL injuries appear to occur in situations involving one or more of the following manoeuvres: foot strike with knee close to full extension [13, 14], landing [15, 16], deceleration [17] and rapid change of direction [18]. For example, in a study by Olsen et al., [14] video tapes of game situations in which ACL injury occurred in team handball were analysed to try to identify the mechanisms for ACL injury. Three handball experts were used to identify possible risk factors such as body position, type of movement, with or without the ball, phase of play, balance, attention, speed and contact. Three physicians were used to identify factors relating to the knee position such as estimated flexion, rotation, varus-valgus angle, foot position and degree of weight bearing on the leg. The most common action being performed at the time of injury was a plant and cut movement (12 of the 20 cases analysed) accompanied by forceful valgus and external-internal rotation with the knee close to full extension. Of these twelve injuries, four occurred during two-foot stance, eight were in single foot stance and all occurred during the push off. The next most common injury mechanism was a one-legged jump shot landing, where athletes were jumping and landing on the same leg. This accounted for four cases and all occurred with a forceful valgus, external rotation and knee close to full extension on landing. Therefore it was concluded that movements that put the ACL at risk involved a single foot stance, forceful valgus knee movement with the knee close to full extension accompanied with external or internal rotation of the tibia. Not surprisingly, the incidence of ACL injury is relatively high in sports such as basketball, netball, handball and volleyball that are characterised by a high frequency of landing, decelerating and rapid changes of direction [5, 14, 19].

2. Gender differences in ACL injuries.

The incidence of non-contact ACL injury in females has been reported to be 6 to 8 times greater than in males competing in the same sports [19-27]. Arendt and Dick [19] reported the incidence of ACL injury in collegiate basketball and soccer for males and females over the period 1989-93. Data was collected for 461 male and 278 female soccer teams and 531 male and 576 female basketball teams. ACL injury was reported in terms of athlete-exposure, where athlete-exposure took into account games and practise sessions. For soccer, female ACL injury incidence of 0.39 per 1000 athlete-exposures compared to 0.13 per 1000 athlete-exposures for males were reported. For basketball, the incidence of ACL injury was 0.29 per 1000 athlete exposures for females and 0.07 per 1000 athlete exposures for males. Malone et al. [24] documented the injuries of 402 male and 385 female basketball players from 29 institutions in three Division 1 collegiate basketball conferences over a five year period. 62 females and 9 males sustained ACL injury, which corresponded to an incidence of 16.1% in females and 2.2% in males.

3. Anatomy of the knee complex.

The knee joint complex consists of two joints: the patellofemoral joint and the tibiofemoral joint. The tibiofemoral joint is the articulation between the proximal tibia and the distal femur. The patellofemoral joint is the articulation between the patella and the anterior femoral condyles.

3.1. The tibiofemoral joint.

The proximal articular surface of the tibiofemoral joint is formed by large medial and lateral condyles of the distal end of the femur (Figure 1 a and b). The two condyles are separated by the intercondylar notch. The articular surfaces of the proximal tibia that correspond to the femoral articular surfaces are two shallow concave medial and lateral condyles.

Figure 1 about here.

The tibiofemoral joint is stabilised by the interaction of dynamic and passive stabilisers. Dynamic stability is provided by the muscles that cross the tibiofemoral joint. These are primarily the quadriceps, hamstrings and triceps surae. Passive stability is provided by the non-contractile structures of the knee. These structures are the joint capsule, lateral and medial menisci and four extracapsular ligaments: lateral ligament, medial ligament, ACL and the posterior cruciate ligament (PCL) (see Figure 1, a and b).

The ACL and PCL are located in the intercondylar notch and cross each other with the ACL passing laterally to the PCL. The distal end of the ACL is attached to the posterior aspect of the anterior intercondylar area of the tibial table. The proximal end is attached to the posterior medial aspect of the lateral femoral condyle. The distal end of the PCL is attached to the posterior aspect of the intercondylar area of the tibial table, and the proximal end is attached to the anterior inferior lateral aspect of the medial femoral condyle (see Figure 1, a and b).

3.2. The function of the cruciate ligaments.

The function of the cruciate ligaments is to ensure normal movement between the articular surfaces of the femoral and tibial condyles. Figure 2 shows a free-body diagram of the forces acting on the proximal tibia.

Figure 2 about here

From Figure 2, it can be seen that the ACL and the hamstrings work together to help prevent anterior dislocation of the tibia relative to the femur by resisting forward movement of the tibial condyles (see Figure 3a and b). Similarly, the PCL works with the quadriceps to help prevent posterior dislocation of the tibia relative to the femur by restricting backward movement of the tibial condyles (see Figure 3a and c).

Figure 3 about here.

In addition to helping to prevent posterior dislocation of the femur on the tibia (ACL) and anterior dislocation of the femur on the tibia (PCL), the cruciate ligaments also help prevent hyperextension of the tibiofemoral joint, medial and lateral displacement of the tibia relative to the femur and internal rotation of the tibia relative to the femur. At present, there is little empirical information on the extent to which landing, decelerating and cutting movements cause abnormal movement of the tibiofemoral joint and, therefore, abnormal strain on the ACL and other knee ligaments.

4. Risk factor models.

The risk factors associated with ACL injury in general and the gender difference in ACL injury incidence in particular have been grouped in various ways [5, 6, 28-31]. One of the most frequently used categorisations of injury risk factors is intrinsic-extrinsic. Intrinsic factors are personal, physical and psychological characteristics that distinguish individuals from each other and extrinsic factors concern environmental conditions and the manner in which activities are administered [32]. With regard to ACL injuries, Griffin et al. [5]

categorised risk factors into three intrinsic groups (anatomical, hormonal, biomechanical) and one extrinsic group (environmental). Whereas the main cause of an injury may be apparent, in most cases the cause of the injury is likely to be the result of a complex interaction of intrinsic and extrinsic factors [28]. The main limitation of current models of the aetiology of injury in general and ACL injury in particular is the failure to show how the various risk factors interact. A reasonable first step in trying to understand the interaction between factors would be to describe the relationship between and relative weighting of the various factors. ACL injury is caused by excessive load on the ACL which is due to abnormal movement of the tibiofemoral joint. The latter is due to the failure of the passive and/or dynamic support mechanisms to adequately stabalise the joint; see Figure 4. The purpose of this paper is to present a risk factor model for ACL injury based upon a review of the components of the passive and dynamic support mechanisms.

Figure 4 about here.

5. Passive stability risk factors.

As shown in Figure 5, the passive stability of the tibiofemoral joint depends upon the geometry of the articular surfaces and ligament laxity.

Figure 5 about here.

5.1 Geometry of the articular surfaces

The geometry of the articular surfaces of the tibiofemoral joint depends upon the alignment of the femur with respect to the tibia and the congruence between the articular surfaces of the femur and tibia; see Figure 5.

5.1.1 Alignment of the femur with respect to the tibia

There is considerable evidence that the Q angle, i.e. the acute angle between the line connecting anterior superior iliac spine to the middle of the patella and the line connecting the tibial tuberosity to the centre of the patella [33] is, on average, larger in females than males[34-38]; see Figure 6.

Figure 6 about here.

For example, Herrington and Nester [38] measured the Q angles of 51 male and 58 female physically active subjects with no history of lower limb injury. Q angle was measured with subjects standing and quadriceps relaxed. The results showed mean Q angle to be significantly greater in females (mean Q angle 13.9^o) than in males (mean Q angle 11.5^o). The larger the Q angle, the larger knee valgus angle; see Figure 6. Since increased valgus angle during dynamic movement has been associated with an increased likelihood of ACL injury [13, 14], some studies have investigated the relationship between Q angle and ACL incidence. For example, Shambaugh et al. [39] investigated the relationship between lower extremity alignment and knee injury in 45 recreational athletes. The results showed that athletes who had sustained knee injuries had significantly larger Q angles than the players who had not been injured (mean Q angle in knee injured 14^o, non-injured 10^o). However, there would appear to be no evidence that the increased Q angle in females increases the risk of ACL injury.

5.1.2 Congruence between the articular surfaces of the femur and tibia

Congruence between the articular surfaces of the femur and tibia will depend upon the size and shape of the condylar surfaces of the femur and tibia and the size and shape of the menisci. The femoral condyles (convex in sagittal plane) and tibial condyles (shallow concave in the sagittal plane (see Figure 3) are not very congruent, but in the healthy knee, the congruence between the femoral and tibial condyles is normally quite high due to the menisci; see Figure 1a. Damage to the menisci, especially complete radial tears, has been shown to decrease congruence and decrease passive stability of the joint [40]. However, there would appear to be no empirical evidence of damaged menisci increasing the incidence of ACL injury. The congruence between the femoral and tibial condyles will also be affected by the width of the intercondylar notch (INW); the wider the notch, the lower the congruence; see Figure 7.

Figure 7 about here.

However, the narrower the notch, the smaller the space available for the cruciate ligaments. Some studies have reported that females have a smaller INW [41-43] and NWI (ratio of INW to width of femoral epicondyles) [44] than males. Also, a number of studies have reported greater incidence of unilateral and bilateral ACL injury in subjects with smaller INW [41, 43, 45, 46] and NWI [44, 46]. For example, Uhorchak et al. [43] carried out a four-year study of 711 male and 113 female army cadets. INW was measured at the start of the four-year period via radiographic assessment using digital callipers. During the four-year period 24 non-contact ACL injuries occurred, 16 to males and 8 to females. The results showed INW to be significantly smaller in females (mean INW 15.6mm) compared to males (mean INW 17.7mm) and INW to be significantly smaller in non-contact ACL injured subjects (mean INW 13.8mm) than in non-injured subjects (mean INW 17.5mm).

However, other studies have not found an association between ACL injury and INW or NWI [47-49] and there is no clear evidence that differences in INW or NWI influence the incidence of ACL injury.

5.2 Ligament laxity

Joint laxity refers to the degree of instability in a joint, i.e. the range of movement in directions that are considered abnormal for that joint when no muscles are active [32]. Several studies have reported that females exhibit greater joint laxity than males [50, 51] and knee joint laxity has been proposed as potentially contributing to the greater incidence of ACL injuries in females [21, 43, 50]. It is not clear what causes differences in joint laxity in healthy knees, but it is reasonable to assume that it is due to differences in the length and tensile stiffness (resistance to stretching) of ligaments; see Figure 5. The longer the ligaments and the lower the tensile stiffness, the greater the laxity. The tensile stiffness of a ligament will depend upon the cross sectional area and the effect of circulating hormones on the material properties of the ligament. Some studies have reported that the cross sectional area of the ACL is relatively larger in males than in females [42, 52]. For example, Charlton et al. [42] used magnetic resonance imaging to measure ACL volume in 98 knees of males and females and found that ACL volume was significantly relatively smaller in females than males. However, there is no evidence that cross sectional area of the ACL influences the incidence of ACL injury. The effect of hormones on the material properties of the ACL has been identified as a potential cause of the greater incidence of ACL injuries in females. Due to the identification of oestrogen and progesterone receptors in the human ACL [53], some studies have investigated the effects of the variations in the levels of female sex hormones on the material properties of ligaments [54-56]. For example, Slauterbeck et al. [55] reported that the administration of oestrogen significantly decreased the tensile strength of the ACL in rabbits. These findings suggest that the levels of female sex hormones may affect the strength of the ACL which may provide some explanation for the greater incidence of ACL injury in females. Consequently, several studies have investigated the time of occurrence of non-contact ACL injury in females in relation to the phase of the menstrual cycle [12, 57-59]. Some studies reported significantly higher incidence of ACL injury between days 10-14 [57, 58], whereas others reported significantly higher incidence during days 1-2 of the menstrual cycle [59]. Also, days of significantly lower incidence of ACL injury have been reported between days 1-9 [57], days 8-14 [12] and days 15-28 of the menstrual cycle [58]. The inconsistency of these findings may be attributable to the relatively small samples used. However, on current evidence, the influence of changes in hormone concentrations on the incidence of ACL injuries in females is not clear.

6. Dynamic stability risk factors.

During dynamic movements such as landing and cutting (side-stepping), it is unlikely that the passive structures of the tibiofemoral joint can provide adequate joint stability. Consequently, dynamic stability in the form of muscle activity is necessary to provide adequate joint stability. Figure 8 shows the factors that affect muscle function and, therefore, the dynamic stability of the tibiofemoral joint: the patellar tendon-tibia shaft angle, muscle activity pattern (in terms of net joint torque), muscle reaction time, time to peak torque and muscle stiffness.

Figure 8 about here.

6.1. Patellar tendon – tibia shaft angle

The patella tendon-tibia shaft angle (PTTSA) is the angle (in the sagittal plane) between the long axis of the tibia and the line of action of the patellar ligament (Figure 9). The greater the PTTSA, the greater the anterior shear force exerted by the patellar ligament on the proximal end of the tibia (ASPT). The greater the ASPT the greater the potential strain on the ACL.

Figure 9 about here.

Nunley et al. [60] investigated the effect of knee angle on the PTTSA. Regression analysis showed that the PTTSA decreased linearly in both males and females from 0° of knee flexion to 90° of knee flexion (Table I), i.e. the PTTSA and, therefore, the ASFT was largest when the knee was close to full extension. A number of studies including Boden et al. [13] and Olsen et al. [14] have reported that non-contact ACL injury appears to occur more frequently when the knee is close to full extension than when flexed. Nunley et al. [60] also showed that the PTTSA was, on average, 3.6° greater in females than in males over the 0°-90° range of knee flexion, i.e. for a given angle of knee flexion, the ASPT is likely to be 13.0% greater in females than in males over the 0°-90° range of knee flexion. Therefore, the PTTSA may contribute a greater risk of ACL injury in females than in males.

Table I about here.

6.2 Whole body movement pattern

The patellar tendon-tibia shaft angle depends upon the knee angle which, in turn, depends upon the whole body movement pattern. Kinematic and kinetic analyses of drop-jumps, stop-jumps and cutting movements have been undertaken in order to try to identify movement characteristics that may account for gender differences in the incidence of ACL injuries. A summary of these studies can be seen in Table II. In general, the studies indicate that in landing and cutting manoeuvres, females tend to land with less knee flexion [61-65], exhibit greater knee valgus [61, 66], display greater peak knee extension moments [62, 63] and produce greater normalised ground reaction force [63, 64] when compared to males. As described earlier, these types of movement are likely to increase the load on the ACL. These findings tend to indicate differences in landing and cutting movement patterns between males and females. However, lack of appropriate standardisation in task demands may have invalidated meaningful comparison between females and males. For example, dropping down from a raised platform set at the same height for both males and females [63, 65, 66] may result in significantly different task demands.

Table II about here.

6.3 Muscle activity pattern

When providing dynamic stability of the knee, the activity of the knee flexors and extensors should, ideally, result in a zero shear load on the proximal tibia and, therefore, minimal strain on the knee ligaments. However, if the shear load exerted by the quadriceps is greater than the shear load exerted by the hamstrings, a resultant anteriorly directed shear force may be exerted on the proximal end of the tibia, which will increase ACL strain (see Figure 10). This is known as quadriceps dominance [67]. A number of studies have found that females exhibit greater quadriceps dominance than males in activities associated with ACL injury [51, 61, 68].

Figure 10 about here

Malinzak et al. [61] investigated 3D knee joint motion and EMG activities of the hamstrings and quadriceps in 9 female and 11 male recreational athletes while running, cross-cutting and side-cutting. When cross-cutting subjects, hit a marked area with the dominant foot and changed direction at 45^o to the non-dominant side, whereas side-cutting involved hitting the marked area with the dominant foot and changing direction at 45^o to the dominant side. Surface electromyographic (EMG) signals were recorded during maximum voluntary contraction (MVC) tests for vastus lateralis and vastus medialis oblique and for the biceps femoris and medial hamstrings so that EMG data could be expressed as a percentage of the EMG recorded for MVC. Females exhibited less knee flexion than males throughout the stance phase of all tasks (Mean- females 25^o compared to 29^o for males). Also, females demonstrated on average 11^o greater knee valgus than males throughout the stance phase (males: range -1^o to 6^o; females: range -12^o to -4^o). The EMG data indicated that females had greater quadriceps activation (17-40%MVC greater) yet reduced hamstring activation (20%MVC less) than males. Huston and Wojtys [51] investigated knee activation patterns in response to anterior tibial translation in elite basketball and volleyball players. Females athletes tended to respond to anterior tibial displacement of the knee by firstly contracting the quadriceps, whereas male athletes and male and female non-athletes responded by firstly contracting the hamstrings. Zeller at al. [68] investigated the kinematics and EMG activity of the quadriceps and hamstrings of 9 male and 9 female collegiate athletes while performing a one-legged squat using the dominant limb. Females demonstrated significantly greater ankle dorsiflexion and pronation, hip flexion, adduction and external rotation and reduced lateral trunk flexion than males. Analysis of all muscles tested showed females to display greater total muscle activation than males. Analysis of each muscle independently showed females to produce significantly greater total and maximal activation of the rectus femoris compared to males.

The findings of these studies [51, 61, 68] suggest that, compared to males, females tend to exhibit a quadriceps dominant mode of producing dynamic joint stability of the knee which may increase the risk of ACL injury.

6.4 Muscle reaction time and time to peak torque

Muscle reaction time (RT) and time to peak torque (TPT) clearly affect the speed with which dynamic stability can be achieved and, as such, may affect the likelihood of joint injury [69]. Cowling and Steele [70] investigated the effect of gender on lower limb muscle synchrony during landing in 7 male and 11 female subjects. The task involved subjects accelerating forwards three steps to receive a netball chest pass from 3m directly in front and then land on their dominant limb on a force platform in single limb stance. EMG data was recorded, from the rectus femoris, vastus medialis, vastus lateralis, semimembranosus, biceps femoris and the medial head of the gastrocnemius muscles. The main findings were that males exhibited a delayed semimembranosus onset relative to ground contact (Males 113±46ms, females 173±54ms) and delayed peak activity relative to peak tibiofemoral shear force (Males 54±27ms, females 77±15ms) compared to females. It was suggested that the delayed onset of semimembranosus activity in males allows peak semimembranosus activity to better coincide with high anterior force exerted on the proximal tibia by the quadriceps thereby acting as an ACL synergist via increased joint compression and posterior tibial drawer, reducing the chance of ACL injury.

Wojtys et al. [71] investigated the effect of three types of training on RT and TPT in 16 male and 16 female healthy subjects. Subjects were placed into one of four groups; isokinetic, isotonic, agility and control. The three training groups exercised for 30 minutes, three times a week for 6 weeks, whereas the control group participated only in activities of daily living and the recreational activities they were involved in prior to the study. RT was assessed as the muscular response to an anteriorly directed 30 pound force applied to the posterior aspect of the tibia, with the subject sitting in a relaxed position with the knee flexed at 30°. Surface EMG was recorded for the gastrocnemius, lateral hamstring, medial hamstring, lateral quadriceps and medial quadriceps muscles. The readings from these muscles were then used to calculate three components of RT; spinal reflex (between 26 to 130msec after initiation of tibial displacement), intermediate response (between 110 to 216msec after initiation of tibial displacement), and voluntary muscle activity (between 156 to 431msec after initiation of tibial displacement). The findings showed that the agility exercises resulted in a significant reduction in all three components of RT. Isokinetic training resulted in a significant decrease in the voluntary muscle activity component of RT. No significant improvements in any of the components of reaction time were seen as a result of isotonic training. All groups showed a reduction in TPT in knee extension isokinetic strength test at 60°/sec and 240°/sec after the 6-week training program, with the agility group showing the biggest reduction (39msec). For knee flexion, the agility group again showed the greatest reduction (38msec) with the isotonic group showing an increase (31msec) after training. For ankle plantar flexion during isokinetic strength testing at 60°/sec and 180°/sec, TPT reduced by 15msec for the isokinetic group, with the other two training groups showing an increase in TPT. The findings of this study show that agility and isokinetic training may reduce anterior tibial translation and therefore reduce the risk of ACL injury.

6.5 Muscle stiffness and muscle strength

As the quadriceps and hamstring muscles contract they act in a way to increase the joint contact forces and limit shear movement within the tibiofemoral joint. The ability of the muscles to resist movement within the tibiofemoral joint (maintain a particular joint angle) refers to muscle stiffness. The greater the ability of the muscles of the knee to prevent tibiofemoral shear movement, the less likely the passive structures of the knee, such as the ACL, will be put under strain. Therefore, muscle stiffness may be an important factor in preventing ACL injury. Due to this, a number of studies have investigated the muscular stiffness of males and females to determine its link to the gender difference in ACL injury incidence [72-74].

Granata et al. [72] investigated the muscle stiffness of the quadriceps and hamstrings in healthy subjects (12 male, 11 female). Subjects were required to support their lower leg at 45^o in two positions. The first required the hamstring to support the weight of the leg and the other required the quadriceps to support the weight of the leg. Weights of 0kg, 6kg and a weight corresponding to 20% of maximum voluntary exertion were added to a fixed ankle-foot orthosis with subjects having to maintain the 45^o angle. A sudden transient perturbation was then applied to the lower leg and the resulting knee flexion-extension motion recorded by an accelerometer attached to the heel of the orthosis. Subjects were asked not to attempt to control the natural motion of the tibia after the perturbation and to maintain constant muscle activity, which was measured by EMG electrodes on the quadriceps and hamstrings. The flexion-extension oscillations of the knee were then used to calculate muscle stiffness. After accounting for differences in applied moment resulting from leg mass, females demonstrated reduced muscle stiffness for the quadriceps and the hamstrings for all torque levels compared to males, with results showing females' stiffness to be between 55.8-73.9% of males. Granata et al. [73] continued the work of the previous study to evaluate whether females also demonstrated reduced leg stiffness in functional tasks, such as two-legged hopping, compared to males. Fifteen male and fifteen female healthy subjects took part in the study. Subjects were required to perform repeated two-legged hopping on a force platform. Each trial consisted of approximately 30 hops and subjects were required to hop at three different hopping frequencies of 2.5Hz, 3.0Hz and preferred frequency. Leg stiffness was found to be significantly greater in males than females at all hopping frequencies with females exhibiting 73-81% of the leg stiffness of males. Wojtys et al. [74] investigated the hypothesis that females are less able to volitionally increase the apparent torsional stiffness of the knee by maximally activating the knee muscles. Torsional stiffness is the ability of the muscles of the knee to prevent rotation of the knee joint. There were two groups of subjects. The first group consisted of twelve male and twelve female National Collegiate Athletic Association Division 1 athletes competing in basketball, volleyball and soccer. The second group of subjects was fourteen male and fourteen female collegiate endurance athletes competing in cycling, crew and running. Pairs of subjects from groups 1 and 2 were matched for age, weight, height, body mass index, shoe size, sport and activity level. Testing was performed using a weighted pendulum which applied an 80N force, directed medially, to the lateral aspect of the right forefoot. The resulting internal rotation was measured optically to the nearest 0.25^o. Trials were carried out with and without maximal activation of the quadriceps and hamstring. The maximal rotations of the leg were greater in females than males for trials with (27% greater) and without (16% greater) activation of the knee muscles. Also, females displayed significantly smaller (18%) volitional increase in torsional stiffness of the knee under internal rotation loading than males. This finding was particularly evident in those athletes in group 1, where there was a 42% difference between genders.

The findings of the studies examining the muscle stiffness of the knee suggest that females exhibit less muscular protection of the knee than males when the knee is externally loaded. This suggests that gender differences in the muscular stiffness of the knee may account, at least in part, for the greater incidence of ACL injury in females. However, further investigation into the apparent variation in the stiffness of the knee between males and females of varying athletic levels is needed to validate this.

One factor that may influence muscle stiffness is muscle strength. A number of studies have reported significantly lower muscular strength of the hamstrings and the quadriceps in females compared to males, even when normalised to body weight [51, 63, 75, 76]. This suggests that the lower levels of muscle stiffness exhibited by females compared to males may be due, at least in part, to lower levels of muscle strength (absolute and relative). Lower levels of strength may increase the risk of ACL injury.

6.6 Effects of fatigue on dynamic stability

Fatigue has been suggested as a risk factor for non-contact ACL injury [77-79] due to its affect on lower extremity muscle activity. However, the findings are conflicting. Chappell et al. [77] investigated the effects of fatigue on knee joint kinetics and kinematics of 10 male and 10 female recreational athletes whilst performing drop-jump tasks. The subjects performed three drop-jump tasks before and after undertaking repeated 30m sprints and vertical jumps to fatigue the subjects' lower limbs. The findings showed that both males and females significantly increased the peak proximal tibia anterior shear force and decreased knee flexion on landing when fatigued compared to non-fatigued. Also, after fatigue, males displayed decreased knee varus moment, whereas females showed increased knee valgus moment. Fagenbaum and Darling [78] investigated the effect of fatigue on knee kinematics and muscle activation during jump landings for 6 male and 8 female varsity basketball players. Three landing tasks were performed, one where subjects jumped from both feet as high as possible and landed on the dominant leg, one where subjects jumped down from a 25.4cm high platform and landed on the dominant leg, and finally where subjects jumped down from a 50.8cm high platform and landed on the dominant leg. Each of these tasks were performed before and after subjects were fatigued by using an isokinetic dynamometer. Subjects undertook knee flexion-extension exercises on the dynamometer until they were fatigued to two levels. These were when subjects could no longer produce 50% and then 25% of maximum extensor torque. EMG data for the hamstrings and quadriceps was collected along with knee flexion angle which was measured using a potentiometer incorporated into two freely pivoting orthoplast lever arms placed on the lateral aspect of the dominant knee. The findings showed that females exhibited greater knee flexion angle at ground contact than males. Also, females displayed greater knee flexion accelerations as a result of ground contact than males. These findings were shown for all jumps and all fatigue levels. Quadriceps and hamstring activities were similar in both males and females. Wojtys et al. [79] investigated the effect of hamstring and quadriceps muscle fatigue on anterior tibial translation and muscle reaction time in six male and four female healthy subjects. Subjects undertook knee examination, arthrometer measurements of tibial translation, subjective functional assessment and an anterior tibial translation stress test before and after fatiguing exercise. The muscle recruitment patterns of the hamstrings, quadriceps and gastrocnemius demonstrated no change between fatigued and non-fatigued tests of anterior tibial translation. However, the results showed a 32.5% increase in anterior tibial translation for the fatigued test compared to the non-fatigued test. Muscle responses originating in the spinal cord and cortical level exhibited significant slowing after fatigue of the hamstrings and quadriceps. These findings suggest that muscle fatigue alters the neuromuscular response to anterior tibial translation which, in turn may reduce the dynamic stability of the knee. In general, the results of studies on the effect of fatigue on lower extremity kinematics and kinetics suggest that fatigue may increase the risk of ACL injury. However, there is currently no evidence to suggest that fatigue has a greater effect on the incidence of ACL injury in females compared to males

7 Composite model.

Figure 11 shows a composite model of the passive and dynamic risk factors that affect the stability of the tibiofemoral joint. It is reasonable to assume that the apparent greater incidence of ACL injury in females compared to males is due to the gender differences with regard to some or all of the passive and dynamic stability risk factors. The only evidence (uni-variate correlation based on small samples) in support of gender differences with regard to some risk factors, such as Q angle, joint laxity, INW, NWI, ACL cross sectional area and changes in concentration of circulating hormones, is fairly weak. However, the evidence in support of gender differences is much stronger with regard to some of the dynamic stability factors, especially PTTSA, muscle activity pattern, time to peak torque and muscle stiffness.

Figure 11 about here

---

8. Conclusions and future research.

ACL injury is a common injury which frequently occurs in sport. ACL injuries occur most frequently in non-contact situations with the athlete in single foot stance, forceful valgus knee collapse with knee close to full extension accompanied with external or internal rotation of the tibia. The situation appears to occur in two particular types of movement; landing from a jump on one leg and rapid change of direction initiated on one leg, such as a side-cutting and cross-cutting manoeuvre. ACL injury occurs as a result of a lack of stability provided by the dynamic and passive stability mechanisms of the knee. Current evidence suggests that the greater incidence of ACL injury in females is due to gender differences in the dynamic stabilising structures rather than the passive stability structures. Consequently, future research should investigate these factors and, in particular, the interaction between the factors that affect dynamic stability of the knee.

References.

1. Faegin JA. Isolated anterior cruciate injury. The crucial ligaments. New York, Churchill Livingstone, 1988.

2. Johnson RJ. Prevention of anterior cruciate ligament injuries. The crucial ligaments. New York, Churchill Livingstone, 1988.

3. Smith BA, Livesay GA, Woo SLY. Biology and biomechanics of the anterior cruciate ligament. Clin Sport Med 1988; 12: 637-46.

4. Gottlob CA, Baker CL, Pellissier JM et al. Cost effectiveness of anterior cruciate ligament reconstruction in young adults. Clin Orthop 1999; 367: 378-82.

5. Griffin LY, Angel J, Albohm MJ et al. Noncontact anterior cruciate ligament injuries: risk factors and prevention strategy. J Am Acad of Orthop Surg 2000; 8 (3): 141-50.

6. Huston LJ, Greenfield ML, Wojtys EM. Anterior cruciate ligament injuries in the female athlete: potential risk factors. Clin Orthop 2000; 372: 50-63.

7. Satku K, Kumar VP, Ngoi SS. ACL injuries: to counsel or to operate? J Bone Joint Surg Br 1986; 68: 458-61.

8. Kannus P, Jarvinen M. Conservatively treated tears of the ACL: long term results. J Bone Joint Surg Am 1987; 69: 1007-12.

9. Irvine LB, Glasgow MM. The natural history of the meniscus in the anterior cruciate insufficiency. J Bone Joint Surg Am 1992; 74: 403-405.

10. Noyes FR, Mooar PA, Mathews DS, et al. The symptomatic ACL-deficient knee. J Bone Joint Surg Am 1983; 65: 154-74.

11. McNair P, Marshall R, Matheston J. Important features associated with acute anterior cruciate injury. N Z Med J 1993; 103: 537-539.

12. Mykelbust G, Maehlum S, Engbretsen L, et al. Registration of cruciate ligament injuries in Norwegian top level team handball: a prospective study covering two seasons. Scand J Med Sci Sports 1997; 7: 289-92.

13. Boden BP, Dean GS, Feagin JA, et al. Mechanisms of anterior cruciate ligament injury. Orthopedics 2000; 23: 573-8.

14. Olsen OE, Mykelbust G, Engebretsen L, et al. Injury mechanisms for anterior cruciate ligament injuries in team handball: A systematic video analysis. Am J Sports Med 2004; 32 (4): 1002-12.

15. Hume PA, Steele JR. Injury prevention strategies in netball: are Australian players heading the advise? In: Abstracts of the Australian conference of Science and Medicine in Sport. Bruce, ACT: Sports Medicine Australia, 1997: 306-7.

16. Otago L, Neal RJ. Netball pivot landings- is there a correct way? In: Abstracts of the Australian conference of Science and Medicine in Sport. Bruce, ACT: Sports Medicine Australia, 1997: 262-3.

17. Miller MDM, Cooper DE, Warner JJP. Review of sports medicine and anthroscopy. Philidelphia, PA, W.B. Saunders, 1995.

18. Bartold SJ. Injury driven change to the fundamental design parameters of the Australian rules football boot. In: Abstracts of the Australian conference of Science and Medicine in Sport. Bruce, ACT: Sports Medicine Australia, 1997: 52-3.

19. Arendt EA, Dick R. Knee injury patterns among man and women in collegiate basketball and soccer. Am J Sports Med 1995; 23: 694-701.

20. Chandy TA, Grana WA. Secondary school athletic injury in boys and girls: a three-year comparison. Physician Sportsmed 1985; 13: 314-16.

21. Gray J, Taunton JE, McEnzie DC, et al. A survey of injuries to the anterior cruciate ligament of the knee in female basketball players. Int J Sports Med 1985; 6: 314-16.

22. Ferretti A, Papandrea P, Conteduca F, et al. Knee ligament injuries in volleyball players. Am J Sports Med 1992; 20 (2): 203-7.

23. Paulos LE. Why failures occur symposium: Revision ACL surgery. Presented at the American Orthopedic Society for Sports Medicine. Eighteenth annual meeting. San Diego, July 1992.

24. Malone TR, Hardaker WT, Garrett WE, et al. Relationship of gender to anterior cruciate ligament injuries in intercollegiate basketball players. J South Orthop Assoc 1993; 2: 36-9.

25. Lindenfeld TN, Schmitt DJ, Hendy MP, et al. Incidence of injury in indoor soccer. Am J Sports Med 1994; 22 (3): 354-71.

26. Irelan ML. Special concerns of the female athlete. Sports injuries: mechanism, prevention and treatment. (2nd Edition). Philadelphia, PA, Williams & Wilkins, 1994: 153-187.

27. Gwinn DE, Wilckens JH, McDevitt ER et al. The relative incidence of Anterior cruciate ligament injury in men and women at the United States naval academy. Am J Sports Med 2000; 28: 98-102.

28. Lysens R, Steverlynck A, Van den Auweele Y, et al. The predictability of sports injuries. Sports Med 1984; 1: 6-10.

29. Lorenzton R. Intrinsic factors. In: Ditrix A, Knuttgen HG, Tittel K, eds. The Olympic Book of Sports Medicine, Oxford, England, Blackwell Scientific, 1988.

30. Nigg BM. Extrinsic factors. In: Ditrix A, Knuttgen HG, Tittel K, eds. The Olympic Book of Sports Medicine, Oxford, London, Blackwell Scientific, 1988.

31. Yu B, Kitkendall DT, Garrett WE. Anterior cruciate ligament injuries in female athletes: Anatomy, physiology and motor control. Sports Medicine and Arthroscopy Review 2002; 10: 58-68.

32. Watkins J. Structure and Function of the Musculoskeletal System. Champaign, IL., Human Kinetics, 1999.

33. Hungerford DS, Barry M. Biomechanics of the patellofemoral joint. Clin Orthop 1979; 144: 9-15.

34. Horton MG, Hall TL. Quadriceps femoris angle: Normal values and relationships with gender and selected skeletal measures. Phys Ther 1989; 69: 897-901.

35. Hsu RWW, Himeno S, Coventry MB, et al. Normal axial alignment of the lower extremity and load bearing distribution at the knee. Clin Orthop 1990; 255: 215-27.

36. Woodland LH, Francis RS. Parameters and comparisons of the quadriceps angle of college-aged men and women in the supine and standing positions. Am J Sports Med 1992; 20: 208-11.

37. Guerra JP, Arnold MJ, Gajdosik RL. Q angle: Effects of isometric quadriceps contraction and body position. J Orthop Sports Phys Ther 1994; 19 (4): 200-4.

38. Herrington L, Nester C. Q-angle undervalued? The relationship between Q-angle and medio-lateral position of the patella. Clin Biomech 2004; 19 (10): 1070-1077.

39. Shambaugh JP, Klein A, Herbert JH. Structural measures as predictors of injury in basketball players. Med Sci Sports Exerc 1991; 23: 522-7.

40. Williams PL, Bannister LH, Berry MM, et al (eds). Gray's Anatomy 1995. Edinburgh: Longman.

41. Shelbourne KD, Davis TJ, Klootwyk T. The relationship between intercondylar notch width of the femur and the incidence of anterior cruciate ligament tears. Am J Sports Med 1986; 26: 402-8.

42. Charlton WPH, St John TA, Ciccotti MG, et al. Differences in femoral notch anatomy between men and women - A magnetic resonance imaging study. Am J Sports Med 2002; 30 (3): 329-33.

43. Uhorchak JM, Scoville CR, Williams GN, et al. Risk factors associated with noncontact injury of the anterior cruciate ligament: A prospective four-year evaluation of 869 West Point cadets. Am J Sports Med 2003; 31 (6): 831-42.

44. Souryal TO, Moore HA, Evans P. Bilaterality in anterior cruciate ligament injuries: Associated intercondylar notch stenosis. Am J Sports Med 1988; 16: 449-54.

45. Lund-Hanssen H, Gannon J, Engbretsen L, et al. Intercondylar notch width and the risk of anterior cruciate ligament rupture: a case control study in 46 female handball players. Acta Orthop Scand 1994; 65: 529-32.

46. Ireland ML, Balantyne BT, Little K, et al. A radiographic analysis of the relationship between the size and shape of the intercondylar notch and anterior cruciate ligament injury. Knee Surg Sports Traumatol Arthrosc 2001; 9 (4): 200-5.

47. Schichendantz MS, Weiker GG. The predictive value of radiographs in the evaluation of unilateral and bilateral anterior cruciate ligament injuries. Am J Sports Med 1993; 21: 110-3.

48. LaPrade RF, Burnett QM. Femoral intercondylar notch stenosis and correlation to anterior cruciate ligament injuries: a prospective study. Am J Sports Med 1994; 22: 198-203.

49. Teitz CC, Lind BC, Sacks BM. Symmetry of femoral notch width index. Am J Sports Med 1997; 25: 687-90.

50. Hutchinson MR, Ireland ML. Knee injuries in female athletes. Sports Med 1995; 19: 288-302.

51. Huston LJ, Wojtys EM. Neuromuscular performance characteristics in elite female athletes. Am J Sports Med 1996; 24: 427-36.

52. Muneta T, Takakuda K, Yamamoto H. Intercondylar notch width and its relation to the configuration and cross-sectional area of the anterior cruciate ligament. Am J Sports Med 1985; 25: 69-72.

53. Liu SH, Al-Shaikh R, Panossian V, et al. Primary immunolocaliization of estrogen and progesterone target cells in the human anterior cruciate ligament. J Orthop. Res 1996; 14: 526-33.

54. Liu SH, Al-Shaikh R, Panossian V, et al. Estrogen effects the cellular metabolism of the anterior cruciate ligament: a potential explanation for female athletic injury. Am J Sports Med 1997; 25: 704-9.

55. Slauterbeck J, Clevenger C, Lundberg W, et al. Estrogen levels alters the failure load of the rabbit anterior cruciate ligament. J Orthop. Res 1999; 17: 405-8.

56. Yu B, Liu SH, Hatch JD, et al. Effect of estrogen on cellular metabolism of the anterior cruciate ligament. Clin Orthop 1999; 336: 229-38.

57. Wojtys EM, Huston LJ, Lidenfeld TN et al. Association between the menstrual cycle and anterior cruciate ligament injuries in female athletes. Am J Sports Med 1998; 26 (5): 614-9.

58. Wojtys EM, Huston LJ, Boynton MD, et al. The effect of menstrual cycle on anterior cruciate ligament injuries in women as determined by hormone levels. Am J Sports Med 2002; 30 (2): 182-8.

59. Slauterbeck JR, Fuzie SF, Smith MP, et al. The menstrual cycle, sex hormones, and anterior cruciate ligament injury. Journal of Athletic Training 2002; 37 (3): 275-8.

60. Nunley RM, Wright D, Renner JB, et al. Gender comparison of patella tendon tibial shaft angle with weight bearing. Research in Sports Medicine: An International Journal 2003; 11 (3): 173-85.

61. Malinzak RA, Colby SM, Kirkendall DT, et al. A comparison of knee joint motion patterns between men and women in selected athletic tasks. Clin Biomech 2001; 16: 438-45.

62. Chappell DJ, Yu B, Kirkendall DT, et al. A comparison of knee kinetics between male and female recreational athletes in stop-jump tasks. Am J Sports Med 2002; 30 (2): 261-7.

63. Salci Y, Kentel BB, Heycan C, et al. Comparison of landing maneuvres between male and female college volleyball players. Clin Biomech 2004; 19 (6): 622-8.

64. James CR, Sizer PS, Starch DW, et al. Gender differences among sagittal plane knee kinematics and ground reaction force characteristics during a rapid sprint and cut maneuver. Res Q Exerc Sport 2004; 8: 31-9.

65. Decker MJ, Torry MR, Wyland DJ, et al. Gender differences in lower extremity kinematics, kinetics and energy absorption during landing. Clin Biomech 2003; 18: 662-9.

66. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. Med Sci Sports Exerc 2003; 1745-50.

67. Hewett TE, Myer GD, Ford KR. Prevention of anterior cruciate ligament injuries. Current women's health reports 2001; 1: 218-24.

68. Zeller BL, McCrory JL, Ben Kibler W, et al. Differences in kinematics and electromyographic activity between men and women during the single-legged squat. Am J Sports Med 2003; 31 (3): 449-56.

69. Beard DJ, Dodd CA, Trundle HR. Proprioception enhancement for anterior cruciate ligament deficiency. J Bone Joint Surg Br 1994; 75: 654-9.

70. Cowling EJ, Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. J Electromyogr Kinesiol 2001; 11: 263-8.

71. Wojtys EM, Huston LJ, Taylor PD, et al. Neuromuscular adaptations to isokinetic, isotonic and agility training programs. Am J Sports Med 1996; 24 (2): 187-92.

72. Granata KP, Wilson SE, Padua DA. Gender differences in active musculoskeletal stiffness. Part I. Quantification in controlled measurements of knee joint dynamics. J Electromyogr Kinesiol 2002; 12 (2): 119-26.

73. Granata KP, Padua DA, Wilson SE. Gender differences in active muscle stiffness. Part II. Quantification of leg stiffness during functional hopping tasks. J Electromyogr Kinesiol 2002; 12 (2): 127-35.

74. Wojtys EM, Huston LJ, Shock HJ, et al. Gender differences in muscular protection of the knee in torsion in size-matched athletes. J Bone Joint Surg Am 2003; 85 (5): 782-9.

75. Kanehisa H, Okuyama H, Ikegawa S, et al. Sex difference in force generation capacity during repeated maximal knee extensions. Eur J Appl Physiol 1996; 73: 557-62.

76. Hakkinen K, Kraemer WJ, Newton RU. Muscle activation and force production during bilateral and unilateral concentric and isometric contractions of the knee extensors in men and women at different ages. Electromyogr Clin Neurophysiol 1997; 37: 131-42.

77. Chappell DJ, Yu B, Kirkendall DT, et al. The effects of lower extremity muscle fatigue on knee joint kinetics and kinematics in stop-jump tasks. Am J Sports Med. In press.

78. Fagenbaum R, Darling WG. Jump landing strategies in male and female college athletes and implications of such strategies for anterior cruciate ligament injury. Am J Sports Med 2003; 31 (2): 233-40.

79. Wojtys EM, Wylie BB, Huston LJ. The effects of fatigue on neuromuscular function and anterior tibial translation in healthy knees. Am J Sports Med 1996; 24 (5): 615-21.

Table I. Mean and range of patellar tendon-tibia shaft angle (PTTSA) in male and female recreational athletes over the 0^{o}*-*90^{o} *range of knee flexion (from Nunley et al.,* [60]*).*

	Mean*	Knee Flexion	Range of PTTSA
Males	22.0^{o}	0^{o}	12.2^{o} to 27.8^{o}
		90^{o}	-11.3^{o} to -0.1^{o}
Females	25.7^{o}	0^{o}	13.3^{o} to 34.8^{o}
		90^{o}	2.1^{o} to 5.4^{o}

**Mean patellar tendon-tibia shaft angle over the* 0^{o}*-*90^{o} *range of knee flexion.*

Table II. Summary of recent studies that investigated the kinematics and kinetics of landing and cutting manoeuvres in males and females.

	Subjects	Level	Task	Results
Salci et al [63]	8F-8M	University volleyball	Vertical landing	Females displayed reduced knee and hip flexion angles at ground contact, greater peak knee extension moment and greater normalised ground reaction force
Decker et al [65]	9F-12M	Recreational volleyball and basketball	Vertical landing	Females had reduced knee flexion at ground contact, greater range of motion and greater peak angular velocities of ankle, hip and knee in sagittal plane. Females showed greater energy absorption and peak powers in the knee extensors and ankle plantar flexors
Chappell et al [62]	10F-10M	Recreational	Forward, backward and vertical jump landing	Females landed with reduced knee flexion and had greater proximal tibia anterior shear force, greater knee extension moments and greater knee valgus moments
Ford et al [66]	47F-34M	High school basketball	Drop Vertical Jump	Increased knee valgus motion and maximum angle in females
Malinzak et al [61]	9F-11M	Recreational	Cutting	Females displayed reduced flexion, greater knee valgus angle and greater quad activation
James et al [64]	19M-19F	High school and collegiate basketball	Cutting	Females displayed greater ground reaction force at maximum knee flexion, reduced knee flexion at ground contact and greater range of knee flexion during stance phase