The Effect of Maturation on the Risk of ACL Injuries in Female Athletes

A Review of Scientific Literature

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Preface

This professional assignment project aims to methodically and systematically analyse evidence based literature and provides relevant information to understand changes in female athletes after maturation that are associated with an increased risk for ACL injuries. All aspects of this work presented are original and our own except as acknowledged in the text.

Throughout this work an enormous amount of support and assistance has reached us from several people. Now we truly understand the meaning of believing in ourselves.

We thank all our fellow students for their amazing support and advice. Our client Ies Monas for his interest and cooperation in our project and great believe in us!

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Introduction

Anterior Cruciate Ligament (ACL) injuries are among the most common knee injuries in sports (Yu et al. 2005). The majority of ACL injuries in sports occur in the absence of physical contact with other players also called non-contact episode, typically during deceleration, lateral pivoting, or landing tasks that are often associated with high external knee joint loads (Hewett et al. 2005). Female adolescents who participate in pivoting and jumping sports suffer ACL injuries 4 to 6-times more than male adolescents participating in the same sports. In particular, female athletes at both the collegiate and high school levels have demonstrated an increased susceptibility to ACL injuries compared to male counterparts (Yu et al. 2005).

Epidemiologic evidence suggests that as adults mature, they experience a decreased chance of fracture and an increased chance of ligament sprain in the lower extremity (Quatman et al 2006). Many studies have linked pubertal stage to type and incidence of injury showed in children and adolescents. Michaud et al (2001) reported that as children pass through maturation stages, both girls and boys show an increasing occurrence of sport injury. Also it is shown that ACL injuries are less frequent in prepubescent children than in adolescents, and no gender-related differences in ACL ruptures have been demonstrated before puberty (Andrish, 2001).

The mechanism underlying gender discrepancies in ACL injury risk is likely multifactorial in nature (Hewett et al. 2006). Four factors have been proposed as potential causing factors: anatomical, hormonal, neuromuscular and biomechanical (Quatman et al. 2006). The anatomical factors as height, femoral length, and femoral notch width have been related to increased risk, but although these factors may contribute to ACL injury risk, they can not be modified. Hormonal factors, such as follicular and ovular phases of the menstrual cycle, have been also related to ACL injury risk, but once more, the extent to which these factors can be modified remains unclear (Hewett et al. 2005). Neuromuscular and biomechanical factors gained recently more interest, after many studies have related a poor or decreased neuromuscular control of lower limb biomechanics, in particular the knee joint during sport related manoeuvres, as a primary contributor to ACL injuries in females.

According to Hewett et al. (2006), neuromuscular control deficits can be defined as muscle strength, power, or activation patterns that lead to increased joint loads. Several findings of research demonstrate, that a decreased neuromuscular control in female athletes are the cause of increased lower extremity joint loads during sports activities. One neuromuscular factor, which can be termed “ligament dominance” (Quatman et al. 2006), is defined as an imbalance between the neuromuscular and ligamentous control of dynamic knee joint stability. This imbalance in control of dynamic knee joint stability is demonstrated by an inability to control lower extremity coronal plane motion in the lower extremity during landing and cutting. Another neuromuscular control deficit frequently observed in female athletes, which can be termed “quadriceps dominance” (Quatman et al. 2006) is an imbalanced muscle activity, defined as disparity between knee extensor and flexor strength, recruitment, and coordination.

“Neuromuscular patterns in males and females diverge substantially during maturation. Males demonstrate increasing strength, power and coordination..."
with age, that correlate with their maturational stage, whereas, on the average, girls show little change throughout maturation” (Hewett et al. 2006). On the other hand, neuromuscular training of the lower extremity has shown to reduce non contact ACL injury rates in female athletes (Cowely et al. 2006, Noyes et al. 2005 and Hewett et al. 1999). Quatman et al. (2006) stated that gender differences, in landing mechanics, force absorption, joint stability and muscle recruitment have shown to reduce by neuromuscular training.

Since pubertal stages may be associated with differences in ACL injury rates, an in-depth examination of the gender differences in neuromuscular performance and its relation with other factors (anatomical, hormonal and biomechanical), that occur during growth, may help identify the specific risk factors that lead to ACL injury rates between between genders, playing an important role in the development of strategies for injury prevention.

Although the difference in ACL injury rates between pre puberty and post puberty athletes is known, a consensus of the specific causing factors is still missing.

This literature review presents the latest findings in scientific researches concerning neuromuscular control differences of the knee joint in the female athlete population before and after puberty compared with male athletes, and the relation with the risk of ACL injury.

Our research aims to answer the question: What is the Effect of Maturation on the risk of ACL Injuries in Female Athletes?
Factors Influencing ACL Mechanisms of Injury

The following chapters will show the role of intrinsic factors (within the body) which have been hypothesized as influencing the risk of ACL injury.

Anatomical Factors

The ACL is an intracapsular structure positioned within the intercondylar notch. Its function is to resist excessive anterior translation of the tibia, extreme varus, valgus and axial rotation, and to stabilize the knee during extended positions, together with the posterior capsule, collateral ligament and hamstring muscles (Neumann, 2002). Differences in anatomical alignment between genders have been suggested as causes of the disparity in anterior cruciate ligament injury rates. A larger Quadriceps femoris angle (Q-angle) may be associated with increased knee valgus during movement resulting in anterior cruciate ligament strain (Pantano et al. 2005). The magnitude of the Q-angle, the degree of static and dynamic knee valgus, foot pronation, body mass index (BMI), the width of the femoral notch and its relation with the ACL geometry are anatomical factors being associated with an increased risk for noncontact ACL injury (Griffin et al. 2006).

Anthropometric Differences and Body Mass

As the child grows, anthropometric parameters of physical variations, such as body height, body mass and limb length, significantly develop every year (Kellis et al. 1999). Myer et al. (2005) argue that there might be a relation of lower extremity bone length with increased risk of ACL injury; possibly due to a longer lever and potential increases in torque at the knee joint (Quatman et al. 2006). However, a rapid increase in growth leads to increased injury rates in both genders and anatomical measures often do not correlate with dynamic injury mechanisms, therefore the potential impact of research into these mechanisms is small and the available literature does not give further information about bone alignment and ACL injury risk factors in pre-puberty female athletes. Knapik et al. (2001) performed a prospective study of risk factors associated with sport related injuries among females and males in basic combat training, on which they did not find a relation with BMI (body mass index) and injury in female military recruits. Ostenberg and Roos (2000) also could not state a positive correlation between BMI and injuries in female soccer players. To date, there is little evidence of the effect of body mass on ACL injuries. It remains unclear, whether BMI can be a cause of ACL injury risk in female athletes.

Increased Quadriceps Angle and Pelvis Width

It is generally agreed that excessive pronation of the foot can contribute to the incidence of ACL injury by increasing internal tibial rotation (Allen & Glasoe, 2000, Bonc, 1999 and Louden & Jenkins, 1996), and both together, foot pronation and Q-angle, will more likely result in ACL injury than just the magnitude of pronation alone.

Anatomically, women have a relatively wider and differently shaped pelvis. That could lead to an increased Q angle. This angle differs between genders; for women the angle is in range 15.8° compared to 11.2° in range to man (Neumann, 2002). Increased Q-angle due to bony alignment between the pelvis
and knee joint, which is a possible factor contributing to excessive lateral tracking of the patella (Livingston 1998) will increase genu valgus (Neumann, 2002).

Gray et al (1985), found in a study on female basketball players, that the factor of Q-angle alone did not correlate with ACL injuries. More recently, Pantano et al. (2005) stated that a larger Q-angle and the increased knee valgus positioning during movement is associated with increased risk for ACL injury. However, Hewett et al. (2006) stated that most studies did not take dynamic testing into consideration and that static Q-angle does not appear to be predictive of either valgus or ACL injury during dynamic movements. Hence, there is no consensus in scientific literature concerning correlation of larger Q-angle and high ACL injury risk. However, a larger Q-angle alignment causes a greater knee valgus angle that together with reduced muscular function might predispose the female athletes to ACL injury.

**Figure 1:** The Q-angle is termed by the line connecting the anterior superior iliac spine and the midpoint of the patella, and the line connecting the tibial tubercle and the same point on the patella (Hungerford & Barry, 1979).

*Decreased Intracondylar Notch Width*

Emerson et al. (1993) hypothesized that a narrow intercondylar notch predisposes the female knee to ACL injury in association with a smaller and therefore weaker ACL compared to males.

It has not been specified whether a small size of the ACL is characterized by less length or less diameter. A shorter ACL would theoretically tighten sooner during tibial translations than a longer ligament. A thinner ACL would have reduced potential to function as a passive restrain for dynamic motion than a thicker ligament.

Since the 1990s much effort has been put upon finding the relation between the high risk for ACL injury in female athletes, the stretching of the ligament over a stenotic notch, and the narrow intercondylar notch.

A small notch is associated with a small ACL, but gender is not the factor- it is just that more females than males have small notches (Shelbourne et al., 1998). Stress in a smaller ACL will be greater for a given applied load as stated by Griffin, (2006). Anderson et al. (2001) found that the ACL area was significantly greater in male than in female athletes, but with adjustments made for body
weight, no significant difference could be determined anymore. Furthermore, no significant correlation of ACL area to notch width in either gender could be found. Therefore the size of the ACL cannot be predicted from the size of the intercondylar notch. The association of notch width and ACL injury was not proven to be causal.

![Figure 2: Comparison of the intercondylar notch width](image)

Figure 2: “A small notch is associated with a small ACL but gender is not the factor - it is just that more female than male have small notches (Shelbourne et al., 1998)”

**Knee Joint Laxity**

In general, female athletes have increased joint laxity compared to male athletes (Boden et al. 2000). Sodermann et al. (2001) found that knee joint laxity and hyperextension significantly increase the risk for injury in female soccer players. In a study of Uhorkach et al. (2003), women with joint laxity displayed a 2.7 times greater risk of ACL injury than those women without laxity. To date, there is little evidence that links an increased laxity with an increased ACL injury in female athletes. Most of the studies regarding knee laxity have been done using static measurements, which may not represent motions where the ligament structures are stressed under dynamic conditions. Therefore, further research on sport related tasks may provide evidence of the consequences under functional conditions.

Griffin et al. (2005) stated that in a selection of athletic college-aged population, a combination of increased body mass, narrow notch width, and increased joint laxity is directly correlated and predictive of ACL injury.

**Hamstring Elasticity and Pelvic Tilt**

Since hamstring muscles play an important role in counteracting the anterior tibial translation by assisting the ACL to reduce this force (Baretta et al. 1988) increased hamstring flexibility could be responsible for the decreased dynamic control of the knee in female athletes (Huston & Wojtys 1996). Lengthening of the Hamstring muscles may slow their neuromuscular response time (Trontelj, 1993) which may reduce its capacity to counteract the anterior tibial displacement during sporting maneuvers.

During and after puberty, in conjunction with remarkable increases in height and weight, males have a significant decrease in flexibility measures (e.g. frequently score lower in sit-and-reach test), whereas females do not (Malina et al. 1991). Hewett et al. (2006) even state that females show an increase in flexibility after maturation.
As female athletes after maturation seem to have more flexible Hamstrings muscles (which are associated with slower response time), it can be stated that as this factor rises in the female population with increasing age, it plays an important role in the mechanisms for ACL injury and should be considered as a factor that might be modifiable by training to create a condition of more muscular stiffness to protect the ACL during anterior tibial translations.

The position of the pelvis dictates the alignment of the lower extremity, in which an excessive anterior tilt of the pelvis causes tightening of the hip flexors, positioning the femur in relative flexion (Loud et al. 1996) and places the hamstrings in an elongated position (Hertel et al. 2004). Hamstring and Rectus Femoris are bi-articular muscles meaning that the rectus femoris acts on hip flexion and knee extension and the hamstrings on hip extension and knee flexion (Kendall et al. 1993). Therefore, a flexion moment at the hip is accompanied by an extensor moment at the knee. A pelvic tilt and increased knee extension moment, have been stated by Louden et al. (1996) to be harmful during deceleration, lateral pivoting, or landing tasks. Hertel et al. (2004) compared twenty subjects with a history of ACL injury and twenty subjects without ACL injury. They found significant correlation of anterior pelvic tilt, with a history of ACL rupture in both gender. Loudon et al. (1996) found that in females, anterior pelvic tilt was significantly related to having a history of ACL injury.

It is proposed that anterior pelvic tilt puts the hamstrings in an elongated position, which yields an less effective function. Furthermore, it appears plausible that female athletes with stronger Quadriceps compared to their Hamstrings show an increased anteriorly tilted pelvis. The pelvic position was associated with ACL injury history in both males and females, hence, this is not a risk factor of ACL ruptures exclusively to females, but as females may have greater anterior pelvic tilt compared to males, it is questionable if it has a relation to ACL injury risks in female athletes.

It is arguable whether pelvic tilt increases in females with maturation, but as Quadriceps strength increases more than the muscle strength Hamstrings, training Hamstring muscles in order to increase their strength may pull the pelvis posteriorly, reducing the anterior pelvic tilt, and flexing the knee, thereby reducing the extended position of the knee joint during sport related manoeuvres.

**Hormonal factors**

Fluctuations in sex hormones during the menstrual cycle have been studied as a risk factor for ACL injuries in female athletes with varying results, implicating both the follicular and ovulatory phase as the time of highest risk. As females before menarche do not have the hormonal drive coming along with the menstrual cycle, Dugan (2005) argues that the role of sex hormones may influence the structure and function of the human ACL, perhaps compromising knee load bearing and proprioceptive feedback. According to Liu et al. (1997), increasing the concentration of estrogen (which occurs in women during their follicular phase as the follicle grows) in a model of ACL tissue-cultures, resulted in decreased fibroblast and procollagen production altering its mechanical properties (viscoelastic and tensile properties), suggesting a possible relation with the risk of injury, but these tests were not performed in vivo. Contrary findings however were found years later on a similar study by Warden et al. (2006) which revealed no significant effect of estrogen treatment on the above mentioned mechanical properties.
Wojtys et al. (1998) demonstrated a trend toward an increase in non-contact ACL injuries during the ovulatory phase of the menstrual cycle and a decrease in these injuries in the follicular phase of the cycle. However, this study has limited reliance on athletes history provided to the medical staff regarding the information of point in time of the menstrual cycle of athletes when the injuries occurred. Slauterbeck et al. (2002) tried to avoid this inaccuracy by using the athlete’s saliva to determine the sex-hormone profile to verify the cycle day of the athletes at the time of injury. They reported the highest number of ACL injuries occurring during days 1 and 2 of the menstrual cycle. Contrary to these findings, Karageanes et al. (2000) found no evidence that hormonal level changes coincide with significant ACL laxity changes in competitive adolescent female athletes. Van Lunen et al. (2003) published similar findings in healthy female subjects, they did not find correlation between follicular-, ovulatory-, and luteal-phase hormonal concentrations and ACL laxity.

Based on the results described above, female sex hormones seem not to have a strong correlation with the risk of ACL injury.

**Neuromuscular Factors**

The function of the ACL is to restrain anterior tibial translation and helps to guide the movement between tibia and femur of the knee joint (Neumann, 2002). Several studies have been carried out to analyze the role of dynamic muscle activity in the knee joint of athletes participate in high risk sports regarding ACL injury. When Quadriceps muscles contract they create an anterior shear force on the tibia relative to the femur causing an anterior tibial translation (Ahmad et al. 2006), whereas the hamstring muscles assist the ACL by reducing this force (Baretta et al. 1988).

Joint forces during sports go well beyond the capacity of passive structures, requiring the assistance of active muscle forces to maintain joint equilibrium (Solomonow et al. 1987). Therefore, dynamic co-activation of Hamstrings and Quadriceps muscles is necessary to control that tibial motion during various athletic manoeuvres.

**Decreased Hamstrings- Quadriceps Ratio**

A balance of force (ratio) between Quadriceps and Hamstring muscles is important for normal knee function (Anderson et al. 2001). Quadriceps muscles tend to be dominant in female athletes regarding both, strength and firing patterns (Huston & Wojtys 1996). Decreased ability of female athletes to balance their Quadriceps and Hamstrings musculature, significantly increases the risk of subsequent ACL injury according to Hewett el al (2006), because isolated Quadriceps muscle contraction can produce forces beyond those the ACL may be able to bear.

A significant smaller Quadriceps to Hamstring ratio (discrepancy between Hamstring and Quadriceps muscle strength) for male athletes was found by Anderson et al. (2001) examining concentric muscle strength and endurance in high school basketball players. Females showed weaker Hamstrings compared to Quadriceps musculature.

Ahmad et al. (2006) found significant effects of gender and maturity on Quadriceps and Hamstring strength. Female after puberty had greater Quadriceps to Hamstring ratio than females before puberty and males both before and after puberty. Pre pubescent athletes of both genders had similar Quadriceps to Hamstring ratios. They argue that these findings are attributable to an increase in Quadriceps strength compared with Hamstring strength.
occurring during maturation in females opposed to males. As muscular imbalance can be reduced by muscle training, this factor could be modified.

At low knee-flexion angles (0-30°), the Quadriceps muscles pull the tibia forward and increase stress on the ACL (Myer et al. 2004). Moreover, the contraction of the hamstring musculature with the knee near full extension cannot provide a sufficient posterior shear force on the tibia to resist anterior tibial translations relative to the femur and thereby protect the ACL (Fagenbaum et al. 2003) Hewett et al. (2006) describe that males demonstrate a 3-fold knee flexor moment compared to females when decelerating from landings, what theoretically would allow them to have a more efficient use of their hamstring musculature to decrease the anterior stress on the ACL.

Regarding the influence of maturation on this factor during deceleration of landing tasks, similar findings as those of Ahmad et al. (2006) were revealed in a study by Hewett et al. (2004) with 181 basketball and soccer athletes during a vertical jump drop followed by a two legged maximum vertical jump. They found that male athletes after puberty showed an increase of hamstring peak moments with increasing age compared to a steady value showed in female athlete population during the maturation process. In female athletes of all maturational stages hamstring peak torque was significantly lower than in their counterpart male athletes. Therefore, one effect of maturation is that after girls mature, they have less hamstring muscle force to counteract the anterior pull of quadriceps on the tibia resulting in an excessive load on the ACL.

Because the anterior translation of the tibia may not be sufficiently decreased by the hamstring muscles in females after maturation, and an isolated quadriceps contraction may produce forces that can rupture the ACL, it can be concluded that Hamstring-Quadriceps ratio is an age and gender dependent factor that can predict the risk of ACL injury in the female athlete population.

### Timing of Muscle Activation

Electromyographic studies of Medina et al. (2007) and Chappell et al. (2007) demonstrate gender related differences in the timing of muscle activation during athletic manoeuvres like cutting, landing, side step or stop jump tasks. Preparing for landing with increased quadriceps activation may increase ACL loading while landing (Chappell et al. 2007) because anterior shear force at the proximal tibia is the major ACL loading mechanism (Berns et al. 1992). Although only studies comparing genders have been available, investigating muscle timing during landing preparation can help to understand the movement patterns which lead to increased risk for ACL injury and the development of prevention strategies for noncontact ACL injury (Chappell et al. 2007).

Huston and Wojtys (1996) measured isokinetic dynamometer strength, muscle reaction time, and muscle recruitment order in response to anterior tibial translation in male and female elite athletes and non athletes of both gender. Female athletes respond slower with their hamstring activation to anterior stress on the ACL than male subjects. Medina et al. (2007) found different results by comparing collegiate female and male athletes with non-athletes of both genders. Female and male athletes demonstrated overall earlier muscle activation than female non athletes prior to ground contact. Moreover female non athletes demonstrated later Vastus Medialis muscle activation compared to female athletes but not later than male athletes. This study demonstrated that muscle activation time female athletes compared with male athletes; but not with female non athletes. The difference of timing of muscle activation around the knee between genders could be reduced by athletic training in the female population.
Chappell et al. (2007) found that female recreational athletes had greater voluntary contractions at the beginning of the flight phase but tend to decrease their hamstring activation after landing compared to male subjects. Male athletes had a rapid hamstring increase during the late flight phase compared to females and similar EMG results at landing. In male athletes there seems to be a trend of greater hamstring activation after the foot strike in comparison with female subjects.

It appears that hamstring activation closer to ground contact is a key factor to protect the ACL by increasing the knee flexion angle and reducing the anterior pull of the tibia by activation of the Quadriceps muscle. Information about how muscle timing patterns change during maturation is missing.

**Imbalanced Medial-Lateral Muscle Activation Patterns**

A discrepancy in medial and lateral Quadriceps recruitment observed in female athletes, combined with increased lateral Hamstring recruitment, has been associated to compress the lateral aspect of the knee joint and distracting the medial part of the knee joint. This will create an increase of knee valgus angle, which loads the ACL as stated by Rozzi et al. (1999). The same authors suggest that female athletes demonstrate a disproportional, 4 times greater firing of their lateral Hamstrings compared to male athletes during deceleration of jump landing. Within the same context Myer et al (2005) reported a decreased ratio of medial to lateral Quadriceps recruitment. This may lead to decreased joint compression (Hewett et al. 2006) as Hamstring contraction compresses the knee joint, which limits resistance to dynamic valgus and anterior tibial displacement. This would predispose the female knee to lift off the medial femoral condyle from the tibial plateau, and will increase loads on the ACL when decelerating a landing or cutting- maneuver (Hewett et al., 2006).

The amount of evidence for a discrepancy of medial to lateral knee muscle activation is poor, therefore, a clear definition of imbalanced medial-lateral muscle activation in genders is not possible. However, it seems that the female athlete population tend to recruit their lateral knee muscles more than the medial ones, which may contribute to a valgus angulation of the knee, which is considered to be a contributor to ACL mechanisms of injury. Therefore, more investigation on this possible important factor of contribution to ACL risk of injury is needed. Moreover, reliable information of the influence of maturation on this factor is missing.

**Biomechanical Factors**

**Sagittal plane Mechanisms**


Concerning the effect of maturation on knee flexion angles, Russel et al. (2007) compared knee motion analysis during a self initiated vertical jump, finding no significant developmental difference in sagittal plane motions of the knee. However, Swartz et al. (2005) analyzed hip and knee kinematics on recreational
active subjects during the same jump task, finding that children showed a significant smaller knee and hip flexion angle during landing at maximal ground contact and smaller hip flexion angle at initial contact. Contrary to these findings, Yu et al. (2005) analyzed knee kinematics vs. knee flexion angles in a drop jump task in a population of soccer players between ages 11 and 16. They found a significant decrease in knee and hip flexion angles at initial contact and at maximal knee flexion moment for the female population as age increased, especially after the age of 13 for the hip joint and 14 for the knee joint, compared to males, where the angles remained same with increasing age. Similar to Yu et al. (2005), Hass et al. (2005) found also in a female basketball and soccer athletes population that female before puberty revealed greater knee angle flexion during initial contact and greater peak knee extension moment in three landing tasks- stop jump, vertical jump and lateral jump- from a maximal jump height matched platform.

Based on the literature mentioned above, it can be stated that knee flexion angles decrease during maturation only in the female population; this will caused increase extension moment in the knee during landing, which leads to higher forces in the knee joint, and hence increasing the risk of ACL injury. Nevertheless, sagittal plane motions have been found not to be the main causative factor of ACL injury, but associated with motions in other planes; mainly with the frontal plane (knee valgus) might increase the risk.

Frontal Plane Mechanisms

The gender based differences in ACL injury rates are strongly related to differences in frontal plane knee motions and torques. Kernozek et al. (2005) stated that the majority of the differences in kinematic and kinetic variables during landing between male and female recreational athletes were observed in the frontal plane. Physiologic dynamic valgus torques on the knee can significantly increase anterior tibial translation and load on the ACL several-times (Hewett et al. 2006). As described previously in Anatomical Factors, a relationship has been stated between knee valgus position, increasing Q-angle, anterior shear forces and ACL injuries during landing (Buchanan 2003).

Ford et al. (2006), using high accurate 3D motion analysis techniques, reported that female athletes had greater knee valgus compared to male athletes preparing to execute a cutting manoeuvre. Sigward and Powers. (2007) found also that female athletes (soccer players), had greater knee valgus during early acceleration on the same task. Hewett et al. (2005) found that knee valgus moments and valgus angles (at initial contact and peak values) were significant predictors of ACL injury status. The same authors suggested that knee valgus moments, which directly contributes to lower extremity valgus and knee joint load, predicted ACL injury risk with 73% sensitivity and 78% specificity.

Concerning the differences in pre and post puberty population regarding motions at the frontal plane, a study by Hass et al. (2005) found no significant difference between developmental stages in the magnitude of knee valgus angle after initial contact during three vertical jumping tasks. But contrary to this single study, different outcomes have been shown in many others. Yu et al. (2005) found that both, males and females before the age of 12 had similar valgus knee angles at initial contact and maximal knee flexion, but that growing older males changed to varus and females remained valgus. Also, knee valgus moments in females increased with increasing age and males maintained an unchanged knee varus moment during landing as age increased. Similar findings have been shown by Buchanan (2003) and Hewett et al. (2004), using the same stop-jump task on 181 middle school and high school soccer and basketball athletes. Both studies revealed that following maturation, females
had greater total valgus moment and greater valgus angle than males, which was similar for males and females before puberty.

Based on the results described above, we can state that frontal plane knee motion discrepancies between genders increase linearly with increasing age, in which female athletes increase angles of knee valgus during maturation and male athletes do not. Therefore, we assume frontal plane motions as mayor causative factor for the higher risk of ACL injury in the female athlete’s population.

Transversal Plane Mechanisms

It has been suggested that internal and external knee motions and torques could contribute to the mechanism of ACL injury. As it is mentioned early in this text, pivoting and cutting manoeuvres are tasks of high risk for ACL injuries. During these tasks, transversal motions occur in the knee joint increasing loads of the ACL.

Wojtys et al. (2003) compared the torsion angles after mechanical perturbation in the knee joint, between female and male basketball, soccer and volleyball players. They found that female athletes displayed greater maximal rotations of the leg, in both, passive and active muscle state, and a smaller increase in muscle stiffness during internal rotation loadings. Similar to this finding, Nagano et al. (2007) found that females had greater internal tibial rotation during landing from a 30cm platform compared to male college population. Chappell et al. (2002) did not find significant difference between female and male recreational athletes on knee transversal motions before landing from a vertical-stop maximal jump, but few years later, the same authors found that female displayed greater internal rotation angles than male during landing from the same jump task (Chappell et al. 2007).

Based on the findings, it seems that knee transversal plane motions during landing tasks differ significantly between genders, which leads to increased torsion loads of the ACL. A direct association of transversal motions with ACL injury rates is not stated, but the combination with knee motions in other planes seems to increase the risk in female athletes. Information about changes during maturation concerning transversal motions in the knee is not jet been widely studied.

Summary of Risk Factors

The purpose of this study was to examine all intrinsic factors which have been associated with the increased risk of ACL injury in female athletes compared to males after maturation.

When discussing the role of anatomical factors associated with ACL injury, there is no evidence which defines a consistent association of any factor alone with an increased rate of ACL injury across age and gender. Although in combination, there have been positive predictive outcomes.

The factors of notch width, joint laxity and body mass alone did not show to increase the risk of ACL injury, but in combination seem to be predictive of ACL injury, although, it was not exclusive for the female population.
The Q-angle has been found to be greater in female compared to male. Although, it causes an increase of knee valgus angle, a larger Q-angle was not predictive for ACL injury in female athletes.

An increased flexibility of the Hamstring muscles might be responsible for the decreased dynamic control of the knee. However, an association of this factor with an increase risk of ACL injury has not been evident. Anterior pelvic tilt places the Hamstring muscles in an elongated position on which an effective functioning is reduced. This anterior pelvic tilt was found to be associated to ACL injury but for both genders equal. When combining the increased Hamstring muscle flexibility in females after maturation (which positions the knee in a more extended position) together with an anterior pelvic tilt (that places the hip in a more flexed position) these two factors together are associated to increase the risk of ACL injury in female athletes.

Fluctuations of sex hormones associated with the high risk of injury in the female athlete population, is not consistently defined. Although, ACL injuries seem to occur on an uneven distribution during the hormonal cycle, the evidence is not certain.

Neuromuscular factors play an important role as potentially influencing ACL injury risk in female athletes.

The Quadriceps muscle has been found to produce enough forces to rupture the ACL when working isolated. Females after maturation show an increase in Quadriceps muscle strength compared to Hamstring muscle strength, which will lead to an increased anterior translation of the tibia increasing the load on the ACL, and will place the knee in a more extended position. Therefore, the factor of Hamstring to Quadriceps ratio can be stated as to be causative for ACL injury risk in female athlete population.

It is shown that Hamstring muscle activation closer to ground contact during landing, is a key factor to protect the ACL by increasing the knee flexion angle when landing. Female athletes demonstrate to respond slower with their Hamstring muscles; mostly directly after ground contact compared to male athletes. Therefore, female display less protective mechanisms in the moment of landing coming from a slower activation of their Hamstring muscles compared to male.

Female have a tendency to activate their medial Hamstrings and Quadriceps muscles less than their lateral ones. This discrepancy of pulling forces around the knee might help placing the knee in a more valgus position during landing tasks. However, there is little evidence and more information is needed in order to conclude a difference between gender on this factor and the association to ACL injuries.

In conclusion neuromuscular factors appear to have a high influence of ACL injury risk. A stronger Quadriceps muscle compared to a weaker and slower Hamstring muscle activation, which will increase the anterior translation of the tibia, combined with a stronger pull of the lateral knee muscles, which will increase valgus moments of the knee during athletic tasks are in combination main causes of the high risk of ACL injuries in female athletes.

Concerning the biomechanics of the motions related to ACL injuries in athletes; cutting, landing and pivoting, there is a combination of motions on the three planes (frontal, sagittal and transversal plane). Although, especially the movements that produce a valgus moment or extension moment, when the knee is close to extension, appears to be associated with an increased risk for ACL injury.
Female athletes after maturation display more extended knee angles during landing than males, which would lead to higher forces in the knee joint. Although, sagittal plane knee motions have not been found to be predictive for ACL injury, a more extended position of the knee during landing combined with increased knee motions in other planes and decreased muscle guard increase the risk of ACL injury in the female athlete population.

Knee motions in the frontal plane have shown to be the best predictor for ACL injury. After maturation, female athletes increase knee valgus moments and angles compared to males, which was found to increase the anterior tibial translation and loads on the ACL several-times. Therefore, movement patterns that produce valgus moments in the knee are causative for the increased risk of ACL injury in the female athlete population.

Motions of the knee in the transversal plane lead to an increase torsion of the ACL. Female show to have decreased protective mechanisms to prevent rotational motions on the knee during cutting tasks compared to male. As larger frontal and transversal moments around the knee are found to accompany cutting tasks, and this are manoeuvres associated with higher risk of ACL injury, the association of increased knee motions in this two angles will increase the risk of ACL in female athletes.

Conclusion

After analyzing the effects of maturation on the high risk of ACL injury in female athletes, our results suggest that the factors mostly influenced by maturity are; Hamstring to Quadriceps ratio, timing of Hamstring muscle activation, valgus moments and internal rotation moments of the knee. In real life, as the body works as a whole, all analyzed factors within the study will increase the risk of ACL injury in a certain level.

Relevance

Nowadays females are more active than ever in competitive athletics (Dugan, 2005) and local soccer and handball clubs are gaining more and more members. Hewett et al. (1999) estimated that 2200 ACL ruptures occur each year in US female collegiate athletes. Additionally, they estimated that the total cost for ACL reconstruction and rehabilitation was $ 37 million annually.

Dynamic neuromuscular training applied to the high-risk population has been advised by Myer et al. (2004), Myer et al. (2004) & Riemann & Lephart (2002) as it decrease ACL injury risk and helps more female athletes to enjoy the benefits of sports participation without the long-term disabilities associated with injury. Griffin et al. (2006) state that neuromuscular training including, plyometrics, balance, and technique training, as well as raising the athlete’s awareness of injury biomechanics reduces the ACL risk in female athletes. However, the specific type of exercise program and the duration and intensity proven to be beneficial to decrease the ACL injury risk in female athletes is warranted for further investigation. Also no consensus has been made towards when (in which age), the training should differ for females and males in order to reduce the discrepancies of ACL injury rates in the female athletes after maturation.

Combining the findings of our study with the positive results of neuromuscular training suggested in the literature to decrease gender differences, a training
program designed especially for the female population should started during puberty. The main focus of the training should be on improving the function of the Hamstring muscles (strength and timing of activation) and controlling activation and motor learning (proprioception) during landing, cutting or pivoting manoeuvres (depending on the specific sport demands).
References


