Thesis for the

degree of Master of Science

Trunk and knee biomechanics in boys and girls during sidestep cutting maneuver

Effect of fatigue and side

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HÁSKÓLI ÍSLANDS

Lífaflfræði hnés og búks hjá strákum og stelpum í gabbhreyfingu

Áhrif þreytu og hliðar

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Ritgerð til meistaragráðu

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Ágrip

Markmið: Slit á fremra krossbandi í hné er alvarlegur áverki sem hefur oft mikil áhrif, t.d. vegna skurðaðgerða og margra mánaða endurhæfingar. Kvenkyns íþróttamenn eru mun líklegri til að slíta fremra krossband en karlar og meirihluti allra slita eru án snertingar við aðra þegar einstaklingurinn er að hægja á sér, breyta um stefnu, eða við að lenda á öðrum fæti. Þetta gerist allt samfara stórum ytri kröftum sem verka á liðinn. Ákveðnar hreyfingar og hreyfiaflfræðilegar breytur eru þekktar sem áhættuþættir fyrir sliti á fremra krossbandi en rannsóknir á þessu sviði hafa aðalleg einblínt á einstaklinga eftir kynþroska. Markmið þessarar rannsóknar var að meta hvort munur væri á kynjunum, í hreyfingum í breiðskurðarsniði í hné og búk ásamt kraftvægi í hné og ytri krafti frá jörðu (gagnkrafti) í sama sniði, milli stúlkna og drengja. Þetta var skoðað í lendingarfasanum í hliðarskrefs gabbhreyfingu. Að auki voru áhrif þreytu og hliðar (hægri/vinstri) skoðuð á þessa þætti.

Aðferðir: Alls voru 128 einstaklingar (76 stúlkur og 52 drengir) fengnir til þátttöku frá handbolta- og fótboltaliðum á Reykjarvíkursvæðinu. Eftir að hafa hitað upp á hjóli í 5 mínútur, gerðu þau hliðarskrefs gabbhreyfingu (5 endurtekningar fyrir hvorn fót) þar sem stigið var á AMTI kraftplötu á meðan átta myndavélakerfi frá Qualisys var notað til að taka upp hreyfingar í þrívídd. Eftir að þátttakendur voru þreyttir í 5 mínútur á skautabretti var ferlið endurtekið. Stöðufasinn var skoðaður frá fyrstu snertingu við plötuna og út fyrstu 50% af standfasanum (50% SF). Ásamt lýsandi tölfræði var fjölþáttagreining notuð til að meta hreyfingar og hreyfiaflfræðilegar breytur með tilliti til hliðar (fótar), þreytu og kyns. Marktektarmörk voru sett við 0,05.

Niðurstöður: *Kraftvægi í hné:* Það var marktækur munur á milli kynja á hámarks fráfærslukraftvægi í hné og var það hærra hjá strákum (0,4 Nm/kg miðað við (m.v.) 0,26 Nm/kg; p<0,001). *Hámarks láréttur gagnkraftur:* Marktækt hærri kraftur fannst við þreytu (8,18 N/kg m.v. 7,71 N/kg; p<0,001). *Hreyfing í hné:* Marktækt víxlhrif hliðar og þreytu (p=0,018), og þreytu og kyns (p=0,025), sáust í hreyfingunni í fyrstu 50% af standfasanum (50% SF). Hreyfingin var meiri hægra megin eftir þreytu og voru þau áhrif meiri hjá stelpunum samanborið við strákana. Að auki voru marktækt víxlhrif hliðar og þreytu (p=0,011) á hámarks fráfærslu (valgus) í 50% SF, þ.e. meiri fráfærsluhreyfing hægra megin við þreytuna. Við upphaf standfasa voru megináhrif þreytu og hliðar þar sem hnén voru meira í fráfærslu við þreytu (0,1° m.v. 1,0°; p=0,019) og einnig hægra megin (1,0° m.v. 0,1; p=0,008). *Hreyfingar í búk*: Megináhrif hliðar fundust fyrir hreyfinguna í breiðskurðarsniði vegna meiri hliðarsveigju að stöðufæti vinstra megin miðað við hægra megin (10,1° m.v. 8,7°; p<0,001). Megináhrif þreytu sáust einnig með almennt minni hreyfingu í átt að stöðufæti eftir þreytu (p=0,006). Við upphaf standfasa var hallinn meiri í átt að stöðufæti hægra megin (p<0,001) og meiri halli til hægri eftir þreytu (p=0,050).

Ályktun: Þessar niðurstöður sýna að þreyta hefur áhrif á hreyfimunstur og auki álag á hnéliðinn við hliðarskrefs gabbhreyfingu. Einnig að kynbundinn munur er á milli kynja um og fyrir kynþroska Að auki er hreyfimunstur mismunandi milli hliða og hafa þreyta og kyn þar áhrif á. Þetta bendir til þess að það sé best að byrja forvarnaræfingar fyrir krossbandaslit um og fyrir unglingsárin. Einnig að kyn, þreytu og ríkjandi fót verði að hafa í huga í því samhengi. Frekari rannsókna er þörf á þessum aldurshópi til að kanna hvort forvarnir sem byrja fyrir kynþroska geti haft jákvæð áhrif á hreyfimunstur íþróttamanna og þar með minnkað líkurnar á krossbandameiðslum.

Abstract

Objectives: Rupture of the anterior cruciate ligament (ACL) is a serious, costly and potentially life changing injury that often results in surgery and many months of rehabilitation. Female athletes have much higher incidence of ACL rupture than males and majority of ACL injuries are non-contact in nature. ACL injury predominantly occurs during deceleration, cutting or 1-legged landing maneuvers associated with high external knee joint loads. Certain kinetic and kinematic variables have been identified as risk factors for ACL rupture, but researches have mainly focused on post-pubertal athletes. The aim of this study was to evaluate sex differences for frontal plane trunk and knee angles and frontal plane knee moments in boys and girls athletes during the landing phase of a sidestep cutting maneuver and the effects of fatigue and side on performance.

Methods: Total of 128 participants (76 females and 52 males; age 10-12 years) were recruited from local handball and soccer teams. After 5 minute warm-up on bike, they performed sidestep cutting maneuvers (5 repetitions for each lower limb onto an AMTI force plate) while an eight camera Qualisys system was used to capture 3D motion. After a 5 minute functional fatigue protocol the testing process was repeated. Stance phase (SP) was identified from force plate data and variables of interest analyzed for the first 50% of stance phase (50% SP). In addition to descriptive statistics, mixed model analysis was used to assess kinetic and kinematic variables, in regards to limb, fatigue and sex as explanatory variables. Alpha was set at 0.05.

Results: *Knee moment:* A significant main effect of sex was found for the peak knee valgus moment which was higher in males (0.4Nm/kg vs. 0.26 Nm/kg; $p<0.001$). *Peak horizontal ground reaction force (50% SF):* Significant main effect of fatigue with higher force in fatigued state (8.18 N/kg vs. 7.71 N/kg; $p<0.001$). *Knee angle*: For knee excursion there was a significant interaction of side-fatigue ($p=0.018$) and fatigue-sex ($p=0.025$). This was evident by more excursion on the right vs. left side post fatigue and more excursion by the girls post fatigue compared to boys. For the maximum abduction angle there was a significant interaction of side-fatigue ($p=0.011$) for 50% SP with more fatigue effect on the right side. At initial contact there was a main effect of fatigue and side where the knees moved more into abduction after fatigue ($p=0.019$) and on the right side ($p=0.008$). *Trunk movement*: A main effect of side was found for frontal plane trunk excursion as overall, greater trunk lean was seen to the stance foot on left side (10.1° vs. 8.7°; $p<0.001$). A main effect of fatigue was also seen, with overall less trunk excursion post-fatigue vs. pre-fatigue ($p=0.006$). At initial contact there was greater trunk lean towards the stance foot on right side ($p<0.001$) and more to the right after fatigue ($p=0.050$).

Conclusion: These results indicate that fatigue adversely affects the motion strategy in sidestep cutting and that sex difference already exist before puberty. Also, sides show different motion pattern and are differently affected by fatigue and sex. This suggests that ACL prevention exercises should be implemented during pre or early adolescence and sex, fatigue and leg dominance has to be considered in that context. Further research is needed in this age group to determine whether preventive measures, starting before puberty, can positively influence movement patterns of athletes and reduce risk of ACL injuries.

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Table of contents

List of Figures

List of Tables

List of Abbreviations

50% SP	First 50% of stance phase
50% SF	Fyrstu 50% af standfasanum
ACL	Anterior cruciate ligament
DJ	Drop jump
CNS	Central nervous system
COM	Center of mass
COP	Center of pressure
GRF	Ground reaction force
GRI	Ground reaction impulse
IC	Initial Contact
LR	Loading rate
ML-GRF	The peak horizontal medial lateral ground reaction force
ms	Milliseconds
MU	Motor unit
OA	Osteoarthritis
NMT	Neuromuscular training
RPE	Rated perceived exertion
SD	Standard deviation
SP	Stance phase
VMC	Voluntary muscle contraction
VGRF	Vertical ground reaction force

1 Introduction

1.1 Epidemiology

Rupture of the anterior cruciate ligament (ACL) is a serious and costly injury that predominantly strikes athletes (1, 2). The risk of suffering this injury is quite low in the general population but considerably higher in many team sports (1, 3). In the USA there are an estimated 80.000- 250.000 injuries per year most commonly in young athletes from 15-25 years old (4, 5). In Norway, between 2006-2009, a national registry with 97% compliance revealed that in the 10-19 year age group, the annual incidence of primary ACL reconstructions was 76 per 100 000 girls and 47 per 100 000 boys (6). In the same registry, surgeries for 11-13 year olds were only 8-9 per year or 0.6% of total surgeries performed and the rate for 12-13 year olds was 3.5 per 100 000 citizens. In same context, the age group at the highest risk was for 16-39 years old, or 85 surgeries per 100 000 citizens. This gives a good estimate of the true incidence rate even though it excludes those treated non-operatively (2).

Even though the risk of ACL injuries is higher in sports, the risk is relatively low. The National Collegiate Athletic Association Injury Surveillance System in the United States compiled data for 16 sports (8 men’s and 8 women’s) over 16 years from a sample of colleges and universities (7). More than 50% of all reported injuries were to the lower extremities in both practices and games, with knee and ankle injuries accounting for most of the lower extremity injuries. ACL injury rates were highest in men’s spring football and women’s gymnastics (33 per 100 000 athlete-exposures) (7). In women’s sports, ACL injury rates represented a larger proportion of total injuries than in men’s sports (3.1% vs 1.9%), with women’s basketball and women’s gymnastics topping the list at 4.9% of total injuries. Overall, high-school athletes (14-18 years) have lower rates of ACL injuries than do collegiate athletes (5.5 vs 15 per 100 000 athlete exposures) but with a similar injury distribution across sports. Since 2005, the National High School Sports-Related Injury Surveillance Study in the United States has compiled data on the incidence of ACL injuries in 18 sports. From 2007 to 2012, ACL injury rates were highest in girls’ soccer and boys’ football (11.7 and 11.4 per 100 000 athlete-exposures, respectively) (2).

1.2 Consequences of ACL injury

ACL injury is a life changing event; this often includes surgery and always involves many months of rehabilitation in addition to the process being substantially costly. For the younger population, time lost from school and sport participation can have considerable effects on the athlete’s mental health and academic performance. Although ACL injuries account for 2-6% of all injuries in sport they can count for up to 88% of injuries associated with 10 or more days of time lost from sport participation (2).

Eighty percent of patients who sustain an ACL tear exhibit a concomitant impaction injury to the articular cartilage, and greater than 50% have meniscal tears (8). The long term health consequences of ACL tear are also evident. Studies have shown that those injured, are up to 10 times more likely to develop early onset degenerative knee osteoarthritis (OA). This condition can not only limit one´s sport participation, but also lead to chronic pain and disability. A systematic review by Lohmander et al. (11)

suggest that 10-20 years after diagnosis on average, 50% of those with ACL or meniscus injury have OA in the involved knee. Another study shows that 16% to 19% would have symptomatic knee OA over their lifetime, and 13% to 15% would need total knee arthroplasty (9, 10). The risk is increased especially for those having concomitant meniscal or other ligamentous pathology (11). On the contrary it is controversial if ACL surgery lowers the risk of knee OA (2, 11).

1.3 Mechanism of ACL injuries

Approximately 70% of ACL injuries are non-contact in nature (12). It is well established that the injury predominantly occurs during deceleration, cutting or single leg landing maneuvers associated with high external knee joint loads (12, 13). Quatman et al. (14) published a systematic review in 2010 to identify ACL injury mechanism. They concluded that it is highly probable that ACL injuries are more likely to occur during multi-planar movements, rather than single planar movements.

The kinematics of the knee are complex and include multiple axes of rotation which are constantly changing under physiological loads (15). The ACL crosses the joint obliquely in three planes and inserts proximally from posterior-lateral femur and attaches on the anterior aspect of the tibia just anterior and lateral to the anterior tibial spine. The ligament is considered bipartite consisting of anteromedial and posteromedial bands (16).

It is well established that the ACL is the primary restraint to anterior translation (80-90%) of the tibia relative to the femur (16, 17) and other structures provide no relevant individual support. The greatest anterior translation is between 20-40° of flexion (15). Biomechanical studies have also revealed that sectioning the ACL results in significant increase in internal rotation of the tibia near full knee extension while additional sectioning of collateral ligaments produces no further increase. This has been used to advocate the importance of the ACL to restrain against internal rotation during flexion-extension movement (15). Despite this evidence there is controversy as to whether the ACL restricts tibial internal rotation especially if it is around a centrally-placed axis (16). On the other hand there seem to be growing consensus about internal rotation increasing the tension of the ACL especially if in combination with anterior translation or the valgus rotation (pivot shift) (16). External load like from quadriceps and weight bearing also play a big role here (16).

Inherently it is difficult to measure ACL strain in vivo, but recent cadaveric and computer models of simulated landings have demonstrated that the important factors that place strain on the ligament are; compression, tibial valgus and tibial internal rotation. On the other hand external tibial rotation is not a factor. This work has also demonstrated that mechanical coupling of internal tibial torque and knee valgus results in increased ACL loading and that combined internal rotation and valgus moments result in ACL strains reported near levels for tissue rupture (8, 18).

Video studies of ACL injury mechanism in athletes indicate significantly different average lower extremity and trunk position compared to controls. These findings, along with the in vitro studies, propose that a combination of forces contribute to ACL rupture and likely that external impulsive axial or compressive force is a key factor by buckling the leg along with rapid tibial valgus and internal rotation (13, 19). Studies show that the rupture likely occurs approximately 40 millisecond (ms) after initial contact (IC) (13) and the peak compression load at failure of the ACL of cadavers to be around

3-8000 N from 30-90° extension (19). This strengthens the theory of rapid impulse in relation to ACL injury and not enough synergistic force absorption at initial ground contact. The hip, knee, ankle and foot help to absorb the ground reaction force (GRF) during normal landing and deceleration. The hip muscles assist in the absorption of reaction forces for the upper body weight, while the knee, ankle and foot absorb the GRFs (19).

At IC the individual has most if not all weight on a single lower extremity (20, 21) with the first contact either with the heel, entirely flatfooted or significantly less plantar flexion of the ankle combined with rapid movement into dorsiflexion (22). This flat-footed position, however, is not always significant like in recent video study of male soccer players (20). The knee is relatively straight at IC (13, 20) with the mean angle around 20°. It is either abducted or relatively straight in frontal plane and the tibia externally rotated. In the next sequence the knee flexes, buckles inward or is abducted in valgus motion coupled with internal rotation and seemingly externally rotates after the injury (12, 13, 20, 22). The hip is more flexed at IC (19, 22) and the trunk tends to be laterally flexed over the injured leg. This sets the center of mass (COM) outside the base of foot support (22, 23). In a study utilizing video analysis by Koga et al. (13) based on a model image-matching method, the GRF and sudden change in angular motion reached its peak approximately about 40 ms after IC. This time frame is likely to be when the ACL ruptures. These mechanisms are the same in men and women but the exaggeration of the positioning and movement of the lower extremities and trunk is much greater in women and often called dynamic lower extremity valgus (20, 21).

Dorsiflexed or flat foot position at IC, or rapidly reaching those, reduces the ability of the plantar flexors to absorb force (19). The provocative position of nearly straight knee and flexed hip combined with high compressive force is thought to additionally compromise the ACL. One of the reasons is steep posterior slope of the tibial plateau and the lateral being steeper than the medial. This causes the lateral femoral condyle to slide posteriorly of the tibial plateau more than the medial femoral condyle does under axial compressive force; this increases the relative internal tibial rotation and consequently increases anterior translation of the tibia as demonstrated in vitro and the model experiment by Oh et al. (8, 19). This has also been supported by an in vivo study during dynamic single leg land and cut tasks (8). These studies have demonstrated that both the peak knee valgus angle and peak internal rotation were significantly correlated to the ratio between the medial and lateral tibial slope, dominated by the lateral.

ACL strain can also be augmented by valgus moment or position by compression of the lateral compartment, generating a coupled internal tibial rotation before medial joint space opening can occur (8). But the primary factor being the internal rotation and the valgus second order effect (8, 19). This movement of internal rotation of the tibia and valgus and relative straight knee correlates with kinematic observation by Koga et al. (13). It also relates to the ligament dominance as one of the neuromuscular imbalances as implemented by Hewett et al. (21, 23). It is characterized by use of anatomic (bony configuration and articular cartilage) and static stabilizers (ligaments) to absorb the GRF. Additionally it includes trunk dominance where there is tendency of excess motion of the trunk during landing and cutting, thereby placing the COM outside base of support at IC leading to an exaggeration of the dynamic valgus and increasing the axial load on the lateral side of the knee (21, 23). The contraction of the quadriceps in the near straight knee contributes probably more to the compression force rather than directly to the anterior translation. This is evident from the force vector in this position (19) and can also be related to the hamstring. In other words this relates to the quadriceps dominance advocated by Hewett et al. (21). This is seen more among women, where the quadriceps is contracted to stabilize and stiffen the knee during landing. Simultaneously, activity of posterior chain muscles is reduced (21).

Although there are equivocal results regarding the importance of abduction, recent studies are supporting the multiplane knee valgus collapse as a primary factor contributing to a non-contact ACL injury as demonstrated in the novel in simulation approach by Quatmann et al. in 2014 (24). A recent systematic review by Patel et al. (25) on bone bruises associated with ACL injury, further supports the hypothesis that the multi-planar valgus loading ACL injury mechanism occurs more frequently than a single plane hyperextension, valgus or varus mechanisms. In contrast, Utturkar et al. 2013 (26) did an in vivo MR and fluoroscopy study in 2013, where they demonstrated decreased tension on the ACL in the valgus collapse position in 30° of flexion, internal rotation of the hip and 10° external rotation of the tibia. Lacking in this study, however, was to evaluate effect of the dynamic motion pattern. Another recent study on bone bruises from 2015 by Kim et al. (27) suggests that for the bone bruise pattern studied, landing on an extended knee is a high risk for ACL injury. Extension was accompanied by increased anterior tibial translation (22 mm), internal tibial rotation (15°), and valgus rotation (5°) in the predicted position of injury relative to the MRI position. Controversy over knee abduction and the valgus collapse still remains and the biggest question seems to be whether the position increases the likelihood of injury or whether it occurs subsequent to injury, as there is not always a valgus collapse during injury. A recent video analysis of ACL injuries in professional soccer players, however, demonstrated that knee valgus occurred regardless of the playing situation the injury occurred in (20). This strengthens the case for the concern of knee abduction and ACL injury risk.

1.4 Risk factors of ACL injuries

Risk factors for non-contact ACL injuries are often divided into extrinsic or environmental factors (sport, shoes/surface interaction, weather and footwear) and intrinsic ones that can be further divided into modifiable (neuromuscular and biomechanical) and non-modifiable (anatomical, developmental and hormonal) factors (28). Other classification schemes also exist, like the one established by the Hunt Walley Meeting II (4) and the ACL Research Retreat VI and VII (18, 29) where the variables under consideration are divided into environmental, anatomical and structural, genetic, hormonal, neuromuscular and biomechanical. The focus in this thesis is on the modifiable factors, but at the same time recognizing their entwinement and possible multifactorial mechanisms of noncontact ACL injury (18, 29).

Anatomical and structural

The following primary structural risk factors examined relative to ACL injury are often based on sex comparison and considered non-modifiable.

- ACL structure and geometry: ACL injured females are at a disadvantage when size, strength and mechanical properties of ACL are compared, and women have weaker properties than men (18).
- Knee-joint geometry-tibial plateau: When ACL injured persons are compared to controls, they have greater posterior inferior tibial plateau slopes and evidentially more on the lateral side. In addition, they have reduced depth of the medial tibial plateau. These factors are exaggerated in females and are associated with higher anterior joint reaction forces, greater anterior tibial translation of tibia relative to femur and greater peak anterior tibial translation. This has also been related to the mechanical coupling of abduction and internal rotation, and increased ACL strain (8, 18).
- Knee joint geometry-femoral notch: Smaller femoral notch width is generally reported in ACL injured subjects (18).
- Knee joint laxity: Greater anterior and internal rotation knee laxity and knee hyperextension (genu recurvatum), along with general joint laxity of the knee, have all been reported in ACL injured subjects. These factors are more prevalent in females than men. Those with greater knee joint laxity are also likelier to use high risk landing strategies (18).
- Lower extremity alignment: There is no compelling evidence in the literature linking any one lower extremity alignment factor with ACL injury (18, 29).

Genetic and hormonal risk factor

Studies suggest that genetic sequence variants play role in the multifactorial condition of ACL rupture and that they modulate risk through effects on structural differences and other biological variation (29). The hormonal risk factors continue to be researched. The magnitude and monthly variation in estrogen and progesterone concentration that females experience after puberty is the main focus of these studies. This is based on the fact that the ACL injury has been reported to be greater during the pre-ovulation phase (28). The hormonal influence at this stage is thought to increase laxity and alter knee joint biomechanics for the worse. On the other hand there is controversy regarding this factor and even though females experience substantial aforementioned cyclic changes, it is impossible to screen and identify potentially high risk individuals (28, 30).

Environmental risk factors

Research studies have indicated that factors influencing shoe–surface traction like increased ground hardness, ground coefficient of friction, ground dryness, grass cover and root density and shoe traction, may contribute to ACL injury (28). However, there is no current consensus relating the environmental and shoe–surface interaction to risk factors that contribute to ACL injury. Confounding factors (i.e. biomechanical, neuromuscular, hydration status, among others) need to be better controlled in environmental risk factors studies (28).

Sex and maturation

ACL injury risk begins to increase at age of 12-13 in girls and 14-15 in boys (2, 6). Sex disparity in ACL injury appears around the time of the growth spurt (12-14 years in girls and 14-16 in boys), peaks during adolescence, and then declines in early adulthood (2, 31). Females between the ages of 15-20 years account for the largest numbers of ACL injuries reported (2, 31). When injury rate at the high school level in sports such as soccer, basketball, baseball and volleyball is compared between the sexes, it is 2.5-6 times higher in girls compared to boys. At the college level, the rates are 2.4-4.1 higher for similar sports. At the professional level some data suggests the ACL injury rates for men and women are essentially equal (2, 31). The data suggest that the rate of ACL injury decreases as the female athletes mature and the level of play increases. On the other hand this is not in harmony with other data from professional soccer (32) and professional handball (33) indicating higher rate in females and highest during competition.

Of all injuries in high school athletes, ACL injury rates were 4.6% in females vs 2.5% in males, with the highest rate in girl basketball, soccer gymnastics and volleyball, or 5-6% (2). Girls are less likely to have surgery and less likely to return to sport after surgery. One factor that has caught the attention of researchers is the dramatic increase of participation in sports by females. This is evident in the American High Schools where the numbers have almost doubled every 10 years since the 70´s (From 0,3-3.3 million in 2013) (34). This has led to an alarming increase in the total number of ACL injuries in female athletes (21, 35).

Before puberty, minimal lower extremity biomechanical and neuromuscular differences are detectable between the sexes. After onset of maturation and after puberty, females show measurable neuromuscular imbalances like quadriceps dominance, ligament dominance leg dominance and trunk dominance compared to men (36). Sex differences in neuromuscular protection system have been detected but the role they have in ACL and other injuries remain unclear (37). Below are some of these relevant findings.

1.5 Neuromuscular and biomechanical risk factors of ACL injury

Neuromuscular control refers to unconscious activation of the dynamic restraints surrounding a joint in response to sensory stimuli (20). The neuromuscular system generates movements and determines biomechanics of playing actions. Furthermore, dynamic stabilization via the neuromuscular control system helps to protect the knee joint during dynamic sport-related tasks. This incorporates interaction of feedforward and feedback systems that include information from multiple afferent pathways including vision, hearing and proprioception (38). This information is used to generate timely, coordinated and co-activated muscle contractions for optimal movement and protection of the knee joint (28, 37). When this neuroprotection system is perturbed, or has suboptimal response, it can manifest itself as decreased proprioception (39), balance and postural control (40), delayed muscle contraction, disturbed activation pattern or ratio (39, 41-43), and decreased strength (44). This can influence joint stability and the strain onto passive joint structures. Among factors that are thought to influence this are sex and fatigue.

Neuromuscular controlled biomechanical factors are among the proposed internal ACL injury risk factors that can be modified for prevention of primary as well as secondary injuries through appropriate training programs (45). To set up a successful ACL injury prevention program, one of the principal components is to identify risk factors that have a cause-and-effect relationship with ACL injury, studies still need to identify those better (45). This includes among others, understanding the loading mechanism of the ACL and relating it to results of biomechanical and neuromuscular studies that have identified a variety of knee kinematic and kinetics differences between male and female athletes, as well as injured and un-injured ones (45).

To identify these biomechanical and neuromuscular risk factors of ACL injury, it is common to use simulated sport activities or functional movements (46). These movements are thought to resemble or induce similar patterns and situations seen during the occurrence of real injuries. Additionally the selection of these movements are based on known loading mechanisms of the ACL and thereby they can potentially induce high risk landing strategies. These include various tasks like bilateral and single leg drop jumps (DJ) (46), stop and jump tasks, sidestep and crossover cuts (47-49). On the other hand there have been few prospective studies published that have identified biomechanical or neuromuscular patterns that are related to greater risk of ACL injury. In addition what makes comparison and interpretation between studies difficult is different methodology of research protocols and task specific results they produce.

1.5.1 Neuromuscular risk factors

Proprioception

Proprioception is widely assumed to play vital role in the functional stability of joints (50). The sensory receptors for proprioception, called mechanoreceptors, are located in the skin, muscles, tendons and joint capsule as well as in the ligaments. Mechanoreceptors function as transducers that convert mechanical load in the joint to afferent impulses. This information is integrated for the motor programing required for precision movements and contributes to reflex muscle contraction, providing dynamic joint stability (50). Rozzi et al. (39) demonstrated in their research in 1999 that female athletes inherently possessed greater knee joint laxity and demonstrated a longer time to detect knee-joint motion into knee extension than male athletes. This was interpreted to render the knee less sensitive to potentially damaging forces. Zazulak et al. (40) found that decreased neuromuscular control of the trunk may compromise dynamic knee stability. Trunk displacement after sudden force release was greater in athletes who later sustained knee ligament and ACL injury.

Muscle activation patterns, ratio and strength

Some studies (39, 41-43) have demonstrated different muscle activation patterns in functional movements between males and females. Areas of interest in this field include thigh, hip and trunk musculature. Results of research studies in this field, however, remain equivocal. Greater quadriceps-to-hamstrings ratio in females has been demonstrated in several studies including the study by Sigward and Powers (41), that showed significantly higher relative activation levels of quadriceps compared to hamstrings in female vs. male soccer players during early deceleration of sidestep cutting. This is in accordance with a study by Ebben et al. (42) that demonstrated a hamstring dominant pattern in males. Co-activation of the hamstrings and quadriceps is thought to be one of the factors that may prevent and reduce knee motion and contribute to loads that increase the ACL injury risk. It has been suggested that hamstring recruitment can counter the load onto the ACL induced by the quadriceps and thus provide dynamic knee stability by resisting anterior and lateral tibial translation, and transverse tibial rotation (28). One perspective in this context is a smaller medial-to-lateral activation ratio for both the quadriceps and hamstring muscle groups that has been seen in women (39, 43). Myer et al. (44) found that female athletes sustaining ACL injuries had similar quadriceps strength as did matched males, whereas hamstring strength was decreased in females.

Significantly higher average *gluteus medius* activity was recorded in males compared to females in a single leg forward jump, but not in other lower extremity muscles in a study by Hart et al. (51). This suggests that reduced activity of the *gluteus medius* could produce less resistance to hip adduction and internal rotation. Although Zazulak et al. (52) did not find reduced activity of the *gluteus medius* in their study, they found lower *gluteus maximus* activity and increased *rectus femoris* activity in single leg landing in females, which might contribute to biomechanical risk factors at the knee via greater hip adduction and internal rotation, and a more extended knee and valgus position (52).

Relative joint stiffness and stability

One viewpoint in in this context that needs to be considered is relative joint stiffness and stability. Muscles crossing joints provide stability to that joint, i.e. muscle stiffness or the resistance to dynamic stretch may protect ligaments from rupture when a load is applied (28). Females have shown less muscular stiffness than males, both for anterior and rotational tibial translation in various studies (28). The ACL has receptors that activate the hamstrings when the ligament is placed under stress, although it has also been suggested that the hamstrings are activated under an alternate reflex arc. This highlights the importance of proprioception and the antagonistic role of the hamstrings against the quadriceps that is considered to increase the anterior drawer with its contraction (28). This protective role of the hamstrings and destructive of the quadriceps has been questioned, for instance by Boden et al. (19). He points out the potentially more important axial compression force and small protective and destructive capabilities of the hamstrings and quadriceps, respectively, in the near extended knee position. In addition to protective reflex muscular activity, athletes appear to achieve functional joint stabilization by relying on some form of muscle pre-activation in anticipation of expected joint load, whereby previously experienced muscle activation patterns and joint motions pre-program or "feed-forward" muscle activity (38). This combination permits athletes to routinely stabilize the knee joint against potentially damaging joint forces.

1.5.2 Biomechanical risk factors

To identify risky movement patterns for ACL injury, biomechanical studies measure several variables. These can include kinematics that identify angle of joints at various points before or during stance phase (SP), excursion of joint motion and angular velocity. Kinetic variables include the GRF and calculations of joint moments. Also, there are findings of interactions between these kinetic and kinematic variables.

Vertical landing strategies

Beaulieu and McLean (46) did a systematic review of published literature on sex-dimorphic mechanics during vertical landings (single and double leg drop-jumps). Using strict criteria resulting in the inclusion of 31 articles, they investigated the sex-based differences in explicit knee and hip landing biomechanical variables that were joint angles and moments. The results did not support the general view that significant sex based difference exists in lower-limb landing mechanics. Actually, a lack of agreement was found in the literature for the majority of the variables examined with no differences evident when consensus was reached. The one exception was that women were typically found to land with greater peak knee abduction angles than males. They concluded that knee abduction could plausibly contribute to sex-specific injury mechanism, considering that knee abduction increases ACL loading and prospectively predicts female ACL injury risk (35). Regarding the lack of consensus regarding sex difference for the other variables, they indicated it could arise from study-based variations in test populations and landing tasks, in conjunction with the limited ability to accurately measure lower-limb mechanics via standard motion capture methods (53).

On the other hand Carson and Ford (54) did a systematic review published in 2011 where the main objective was to analyze the frontal plane knee motion and moments between males and females during landing. The main conclusion was that females appeared to land with significantly greater knee abduction compared to men in most of the included studies. The effect size indicating an increase in abduction angle in females was to further strengthen this conclusion.

Plant-and-cut maneuvers

The plant-and-cut maneuver is one of the most common, if not the most frequent, ACL injury movement pattern (13, 20, 55, 56). Although it can be sport and sometimes sex specific, it has been demonstrated to be the most frequent movement pattern in male professional soccer (20), team handball (13, 55) and female basketball (13, 22). This maneuver has consequently been the focus of many biomechanical studies in the search for cause and effect relationship between risk factors and ACL injuries.

Different cutting strategies have been shown to place the lower limb at varying levels of risk for sustaining an ACL injury and sidestep cuts appears to put the athlete at the greatest injury risk when comparing to cuts like a crossover cut (47, 48). In sidestep, the acceleration is to the opposite direction of the planted leg in contrast to crossing one leg over the planted foot and accelerating in the same direction as the push-off leg in crossover cut (47, 48). The difference in how men vs. women perform various cutting maneuvers has not been fully investigated (48). Furthermore, how these different types of cutting are used during game-like situations has not either been studied.

When looking at sidestep cutting, whole body adjustments for deceleration and redirection are necessary during the maneuver. Among the variables that have been examined in this context are the COM with the respect to the center of pressure (COP) as well as the GRF and ground reaction impulse (GRI). GRI represents change in linear momentum, quantified by calculating GRI as the integration of GRF over time. The deceleration is accomplished by placing the COM behind the COP thereby generating a posteriorly directed GRF (57). Consistent with a posterior placement of the COM is ankle plantar flexion and relative knee extension at IC (58-60), in addition to hip (61) and knee extensor moments (60) and increased muscle activity of the *gluteus maximus* (58, 62), quadriceps (58, 63) and plantar flexor muscles (58, 63). This indicates work of the lower extremity muscles to decelerate the body during cutting.

Even though the primary function of the ACL is to prevent anterior tibial translation, modeling work by McLean et al. (64) demonstrated that during sidestep cutting task anterior drawer loads in isolation were not sufficient to injure the ACL and that valgus and internal rotation were essential. The posterior GRF during the deceleration helps to protect the ACL and the quadriceps force is not enough to cause harm. In order to redirect the body towards a new direction it is common to direct the COM from the COP towards the new direction, and during cutting maneuvers this typically generates a medial GRF. Simultaneously, the body and COM is rotated to align with the new travel path (57, 65). Aforementioned frontal and transverse plane hip and trunk mechanics may facilitate redirection. A laterally displaced hip or limb during cutting is consistent with medial-lateral separation of COM and COP (66, 67). Additionally pre-rotation of the limb at IC and rotational movement (external) is thought to contribute to body rotation toward the new direction (61, 68).

Association between factors on drop-jump and sidestep cutting

Research comparing DJ and sidestep cutting have mainly compared the magnitudes of knee joint moments and the outcome is that there is a unclear correlation between frontal plane measures in DJ and sidesteps and the main difference between the two are lower knee flexion angles and larger knee valgus angles and knee abduction moments in sidestep cutting (69). Factor analysis by O´Connor et al. (70) found poor correlation between frontal plane measures in DJ and unanticipated cutting and other variables typically associated with ACL injury risk. Kristianslund et al. (69) also did this comparison but with elite female handball players. Using sports specific cutting method involving catching a ball they demonstrated that the knee abduction moment was 6 times higher in sidestep cutting and poor correlation was between knee abduction moments, but moderate correlation for knee valgus angles between the two tasks. There was a poor correlation between knee valgus angles in drop-jumps and knee abduction moments in sidestep cuts. The conclusion was that the motion patterns for the two tasks had clear differences.

Sex and sidestep cutting

Benjaminse et al. (53) did a systematic review with the purpose to critically review the results of the published literature on sex-related differences regarding biomechanical and neuromuscular movement patterns during plant and cut maneuvers. Of 557 studies identified only seven were included and of those, five were strictly biomechanical (41, 59, 68, 71, 72). Their findings were that biomechanical sex differences were of questionable clinical relevance and quadriceps dominance was not found in women. Their conclusion was that it is questionable whether ACL injuries during aforementioned movement patterns are purely sex related. Furthermore they advise caution in making inferences as the studies were heterogeneous in terms of subjects, study design and had a low statistical power (53).

Planned vs. unplanned sidestep cutting (anticipated vs. unanticipated)

Brown et al. (49) did a systematic review and meta-analysis on knee mechanics during planned and unplanned sidestepping with the notion that unplanned sidestepping more closely emulates game scenarios by limiting decision time, increasing knee loading and challenging the integrity of soft-tissue structures in the knee. The results for kinematic variables were that unplanned sidestepping produced a wide range of small to large increases in knee extension angles, small and moderate increases in knee abduction angles and a small increase in internal rotation angle relative to planned sidestep. For kinetic variables, unplanned sidestepping produced mostly small (small to large) increases in knee flexor moments, small to moderate increases in knee abductor moments and mostly moderate (small to large) increases in internal rotator moments relative to planned sidestepping.

Effect of leg preference and knee mechanics during sidestep cutting

Previous studies have assessed lower limb preference related to the risk of ACL injury and athletic performance. Even though significance between limbs in terms of injury risk has not been consistently observed, limb asymmetries are still thought to pre-dispose athletes to injury (73). Looking closer at ACL injury and limb preference have raised some intriguing results regarding this topic. Brophy et al. (74) discovered that in a cohort of non-contact ACL injured soccer players that majority of males injured their preferred kicking leg (74%), compared to 32% in females. Brown et al. (75) did a study on the relationship between leg preference and knee mechanics during 45° sidestepping in collegiate female soccer players. The differences between the legs were generally small but the non-preferred kicking leg experienced increased power absorption, knee flexion velocity, abduction angle, and internal rotation angle during the weight acceptance compared to preferred leg and peak push of. This may expose the ACL to increased risk of high strain. Weiss and Brown 2015 (73), also did a small study on female field-hockey players that is the first to observe the impact of limb preference and effect of fatigue and anticipation on knee mechanic during dynamic sport task (sidestep-cutting). Their results indicated that the preferred leg was likely to experience increased frontal plane loading whereas the non-preferred limb was more likely to experience increased transverse plane loading during fatigued unanticipated sidestepping. Both legs had similar flexion angles during SP. The authors concluded that both legs could experience increased risk of ACL strain. In summary, the above studies give the indication that there is difference between the movement pattern of non-preferred and preferred leg and they respond differently to fatigue. As the sexes seem to have different rate of ACL injuries between sides this needs to be considered in future studies.

Knee frontal plane biomechanics and relations to trunk motion in sidestep cutting.

Lateral displacement of limb during cutting affects the separation of COM and COP (66, 67). Related to this context is the displacement of the trunk and its effect on knee biomechanics. Consequently, it has been of interest in recent research, especially in connection to the high abduction moment often seen in sidestep cutting. Previous studies on this topic have reported that increased or excessive external knee valgus moment is associated with initial loading pattern of greater lateral directed GRF´s (66) greater hip internal rotation and adduction (66). Wide foot position or cut with the stance foot (67, 76, 77) greater knee valgus angle and lateral trunk flexion away from cutting direction (78) and less trunk rotation away from the stance leg (79). For the knee abduction moment the moment arm seems to be more important than the force magnitude to determine the size of the moment (77). The cut width, knee and hip frontal plane kinematics as well as hip internal rotation affect the moment arm of the GRF in the frontal plane (77). In other words these factors can act to position the knee medially relative to the stance foot, which may increase the moment arm and joint moment. Factors that have similar effect on the moment arm are torso lateral flexion and rotation (78, 79). These studies have also demonstrated that to significantly lower the peak valgus moment at the weight acceptance phase it is best to place the stance foot closer to the body´s midline (67, 76, 77), use toe landing (77) and hold the torso more upright (67, 76, 77). A full body in-silico simulation study by Donnelly et al. (80) also demonstrated similar results as optimized kinematic solution to reduced peak valgus knee torque during the weight acceptance phase was to redirect the whole body COM medially, toward the desired direction of travel.

Prospective cohort studies to identify ACL injury risk factors

A method that has been used in an attempt to identify ACL injury risk factors, is to determine associations of those factors with pre-injury movement characteristics by using prospective cohort studies. In a prospective cohort study by Hewett et al. (35), adolescent female athletes' biomechanics were screened in a drop landing task. Those who went on to ACL injury, had significantly greater knee abduction angle, 2.5 times greater knee abduction moment, 20% higher GRF and shorter stance time. Knee abduction moment predicted ACL injury status with 73% specificity and 78% sensitivity. Smith et al. (81) did a large scale prospective study to identify biomechanical risk factors. They used a method called Landing Error Scoring System (LESS) to evaluate lower extremity movement. Female college and high school athletes performed the jump landing task required, but the LESS score was not found to predict ACL injuries. Another large scale prospective study on military cadets screened lower extremity biomechanics in simulated stop-jump task and identified larger knee abduction angels at IC (10). Decreased trunk (core) neuromuscular control has been suggested to compromise dynamic knee stability (40), as trunk displacement after sudden force release was greater in athletes that later sustained knee ligament and ACL injury. Significant limitations to these studies include a lack of consideration for the ACL loading mechanism and a lack of cause-and-effect relationship between identified risk factors and injury risk (10).

1.6 Fatigue

Fatigue as one of the possibly modifiable neuromuscular risk-factors for noncontact ACL-injuries (28), has caught the attention of researchers for several reasons. One is that numerous authors have reported higher incidence of injuries in different sports towards the end of half or game and, similarly, at the end of practice (82, 83). Sport performance depends on the ability of an athlete to produce and then sustain high levels of physical, technical, decision-making and psychological skills throughout competition (84). Any deterioration of these skills could appear as fatigue. Yet the manner which fatigue is best described and measured is controversial (84).

1.6.1 Definition, mechanism and symptoms of fatigue

Fatigue manifests as decline of sports performance (84) and it can be experienced during variable activities, indicating that there are different forms of fatigue, (84-87). Yet there is some controversy regarding how fatigue is best described, measured and which mechanisms regulate it (84, 86, 88), which has also made it difficult to build a comprehensive model of fatigue (89) (90). Despite this it seems that most authors agree that fatigue is a complex interaction of peripheral (muscles and heart) and central (neural drive) factors (84, 87).

Several physiological and psychophysiological processes potentially interact to evoke multiple symptoms of fatigue, during maximal or submaximal exercise (84, 85). Muscle performance is thought to either decline directly through peripheral fatigue processes or indirectly by central fatigue processes. Decreased voluntary activation of muscle rising from lowered drive from the motor cortex in the brain has been called central fatigue. Further description is a decrease in the number and discharge rates of the motor units (MUs) recruited at the start of muscle force generation. Processes originating in muscle cells and directly impair muscle contractile function and changes in the mechanisms underlying the transmission of muscle action potentials is referred to as peripheral fatigue (84, 85). Neuromuscular fatigue can also be distinguished by different set of sites that contribute to decrease in force generation Hence fatigue may be due to alterations in; (1) activation of the primary motor cortex; (2) propagation of the command from the central nervous system (CNS) to the motor neurons (the pyramidal pathways); (3) activation of the MUs and muscles; (4) neuromuscular propagation (including propagation at the NMJ); (5) excitation-contraction coupling; (6) availability of metabolic substrates; (7) state of the intracellular medium; (8) performance of the contractile apparatus; (9) blood flow. These sites can be distinguished between central (1-3) and peripheral (4-9) (85).

Peripheral factors can be due to changes in the intracellular environment like work above point of increased blood lactate accumulation. Consequences can be accumulation of lactated and hydrogen ions, accumulation of ammonia and increased heat and sweat. Central fatigue encompasses all the supraspinal and spinal physiological phenomena capable of inducing a decrease in motor neuron excitation (85). This decreased excitation from central origin can be from variable factors like depletion of neurotransmitters and other substances such as ammonium ions and glycogen. Hyperthermia can also play a role. Least but not last this can stem from psychological factors (85). It is well accepted that central fatigue appears to contribute more significantly to decrease in force generation during longer lasting and low- intensity exercise (91).

The psychological and decision making inputs can play big role in overall physical performance. A high positive motivation may counteract effects of raised RPE (90) via RPE center or indirectly via the motor cortex (92). Mental fatigue, lower self-efficacy or anxiety may in contrast augment exercise induced rise of RPE to interfere with decision making and/or directly reduce motor output (84).

1.6.2 Injuries and fatigue

There are indications that fatigue increases the risk of injuries, as several epidemical studies have reported higher incidence of injuries in different sports towards the end of a half-game or a game, and similarly at the end of a practice (82, 83, 93-95). In soccer majority of these injuries are non-contact (93, 96) but in collision sports like rugby majority of the injuries occur in collision or tackles, up to 60% (94). On the other hand majority of injuries occur during competition when compared to training, this is unarguably because of more intensity during matches (95, 96). Training load and game congestion are also factors that can increase the injury rate (97, 98). Rugby players exceeding certain training load threshold can be 70 times more likely to test positive for noncontact, soft-tissue injuries (94). These evidence have brought the attention of researchers to the possible cause and effect relationship of fatigue to ACL injuries.

1.6.3 Fatigue and effect on neuromuscular and biomechanical factors related to ACL injuries

Although there is lack of direct epidemiological evidence (99) and prospective studies (37) linking fatigue to increased ACL injury risk, there is indication that fatigue induces changes that can be related to this risk in some neuromuscular and biomechanical factors (18, 28, 99). Fatigue is thought to perturb neuromuscular control of the body and lead to suboptimal detection of and protection from forces that act on joints during sport activities. This can lead to movement strategies that increase the load on articular structures like ligaments and cartilage during dynamic movement. This has been documented with number of kinematic and kinetic alterations in lower extremities and trunk after fatigue (38, 99-102). In addition there is documentation of aberration in muscle function like, timing, magnitude of activation and force production (38, 103-106). Furthermore research show decreased proprioception (50, 107, 108), altered postural control (107, 109) and increased joint laxity with fatigue (38, 105, 110, 111).

When looking at the results of studies regarding the effect of fatigue on neuromuscular and biomechanical factors, there is one important factor worth noting. Protocols in the current literature used to induce fatigue are very different (50, 84, 112-114), roughly they can be divided into A: Isolated muscle fatigue, B: General fatigue protocols or functional fatigue. The isolated ones are movements that are not similar to the functional task that is being analyzed, characters of the sport or sports in which this type of movement occur and often (38, 50, 84). They provide insight into the effects of fatigue of specific muscles or muscle on functional tasks. The feature of functional fatigue protocols is that they fatigue the subjects with movements similar or identical to the task or sport environment being analyzed. The functional or general protocols have also been divided into short with repetition of explosive or agility movements e.g. repetitive jumps with short sprints or step ups (112) and long term (e.g. shuttle running) (115) (112). The results of different types of protocols show great degree of variation across studies. One explanation for this is that the design of the protocols share very few similarities (113, 114). Even though the trend in the literature is toward functional protocols they often have few similarities which makes generalization of the fatigue response questionable. Another factor that complicates this comparison is that the functional tasks and subjects that the fatigue is supposed to effect are variable. This can include among others unilateral and bilateral drop landing and jumps (100, 102, 116) , cutting- maneuvers (47, 48, 102, 117) , general population or athletes (112).

Proprioception

Fatigue seems to affect proprioception both by efferent and afferent pathways (50, 107) . It is theorized that fatigue may impair the proprioceptive and thereby kinesthetic properties of joints by increasing the threshold and the discharge of the receptors. This could for example be the muscle spindle discharge, disrupting afferent feedback and subsequently altering conscious joint awareness (107). Lattanzio (108) demonstrated altered ability of both sexes to reproduce knee squat angle after general fatigue protocol indicating diminished proprioception. This response was also sex specific depending on fatigue protocol type. Miura et al. (50) showed that proprioception in the male knee, more precisely position sense, was reduced with general load (like 5 min uphill running) without diminished voluntary muscle contraction (VMC) of the thigh, compared with no reduction in position sense associated with reduction in VMC with local load. This indicates that the general load caused general fatigue and the reduce position sense is not due to loss of peripheral afferent signal but other factors especially of central processing of proprioceptive signals (50).

Joint laxity

Joint laxity is one feature that research has shown to increase significantly with fatigue and particularly if induced by enough joint and shear forces, done by repetitive stresses at a high strain rate, such as occurs while running, cutting, jumping, and performing other sport participation skills (38, 110). This increased laxity is suggested to be primarily caused because of the viscoelastic characteristics of joint structures and particularly ligaments, like the ACL. Cyclic loading like experienced with these repetitive stresses can elicit substantial creep, elongation and laxity in the ligaments. This is associated with a desensitization of the reflex arcs initiated by the mechanoreceptors present in the ligaments, resulting in an impairment of the proprioceptive and reflexive neuromuscular response, like delayed contraction of the ACL agonist (hamstrings) for instance (105, 111). Schmitz et al. 2015 demonstrated this with increase in anterior tibial translation during simulated lower extremity weight acceptance (111).

Latency or aberrancy in response of muscles

Numerous EMG studies have shown latency or aberrancy in response of muscles after fatigue. Around the knee the considered ACL agonist (hamstrings) and antagonist (quadriceps) have shown this response to fatigue (38, 103-105). The hamstrings, quadriceps and the gastrocnemius musculature have been widely reported to be the primary dynamic knee stabilizers (106). When the stabilizing influence of muscles is not present or disturbed inert internal tissues such as cartilage and ligaments become vulnerable to abnormal forces (103). On the other hand altered activation of the knee muscles is thought to play role in compensatory effort, for instance to enhance shock absorption by more flexion of the knee in the weight acceptance phase. Nyland et al. (106) demonstrated earlier activation of gastrocnemius compared to delay of the quadriceps during crossover cutting after eccentric quadriceps fatigue. This was considered to demonstrate synergistic and compensatory dynamic knee stabilization in closed kinetic chain function during quadriceps fatigue (106).

Postural control

Another related feature in this motor control context is postural control. It apparently becomes perturbed by lower extremity muscular fatigue, especially by proximal muscles like shown in the work of Gribble and Hertel (107). This was also demonstrated by Hassanlouei et al. (109) in 2014 where fatigue (bicycle exercise) had detrimental effect on postural control during unexpected perturbation. They also demonstrated that endurance training (bicycle training) had led to improved postural stability during joint stabilization by improved contractile properties.

Different effects of fatigue on sexes related to neuromuscular factors

Different effects of fatigue on sexes related to neuromuscular factors are apparent. First, generally, women become less fatigued and recover faster than men at the same intensity of muscle contraction (118, 119). On the other hand this sex difference is task specific for several factors, like if the muscle contraction intensity is greater there is less difference. Despite recent developments, there is a tremendous lack of understanding of sex differences in neuromuscular function and fatigability, the prevailing mechanisms and the functional consequences. Both central and peripheral factors and mechanisms play a likely role (118, 119).

1.6.4 Fatigue and effect on biomechanical variables related to ACL injuries

Effect of sex and fatigue on biomechanical variables related to ACL injuries factors.

The relationship of different effects of fatigue and sex on biomechanical variables related to ACL injuries have not been studied extensively. Do the sexes respond differently to fatigue when these biomechanical variables are examined? The studies found covering this topic, mainly focus on DJ except one on sidesteps. The result of these studies by Kernozek et al. (99), McLean et al. (116) and Gehrig et al. (120) raises the question of the effect of general or functional protocol vs. isolated joint fatigue protocol as the former mentioned studies using functional fatigue protocol affect the biomechanical variables better. To summarize the results, pre-fatigue the females were more erect and had more abduction movement and moments in the frontal plane particularly in the knees (99, 116, 120). Post-fatigue, when considering the interaction of sex and fatigue, the women did not bend their knees as much as the men resulting in higher anterior shear forces during functional protocols (99) and the knee peak abduction moment was higher in women (116). On the other hand there is not yet any prospective epidemiologic data to support this association of potential compounding effect of fatigue and sex to support the detrimental effect on women (37).

The one study we found using sidestep to evaluate the interaction of sex and fatigue regarding the biomechanical variables was done by Iguchi et al. 2013 (118). They point out that some studies have examined how the unanticipated condition and fatigue affect landing and sidestep cutting for female athletes. Those results indicate some negative and potentially ACL injury related changes in women like lower hip and knee flexion angles after fatigue. They also mention that there are no studies of how unanticipated condition and fatigue affect sidestep cutting movement in relation to sex. In the study the fatigue was induced by counter- movement jumps protocol. After the fatigue protocol women demonstrated significantly larger impulse of initial GRF during the first 50 ms, compared with men. Primary effects of sex indicated that women demonstrated smaller hip flexion angle at initial contact and at maximal flexion angle. One of the limitation mentioned for the study was that the frontal and transverse plane were lacking, because they are commonly being linked to non-contact ACL injury and the negative effect of sex and fatigue on those variables during cutting tasks (115, 121) two leg landings(120) and video analysis of ACL-injuries (13, 20).

Fatigue and effect on single limb landings and sidestep-cutting

Santamaria and Webster, 2010 (101) did a systematic review on fatigue induced biomechanical changes during single limb landings including 8 studies and calculating effect size. The main results showed some evidence that VGRF's and hip and knee joint moments were reduced with fatigue. Furthermore kinematic changes were less consistent and require further study. On the other hand when the landings were unanticipated there was a significant increase in peak stance valgus angle in one of these studies (102). They pointed out that future studies should focus on developing standardized fatigue protocols that include both local and central fatigue effects and monitor fatigue over time. They also noted that fatigue protocols have been suggested in injury prevention programs. For them to be successful they mention reliable protocols that induce fatigue need to be identified and the effect of fatigue on the motion pattern needs to be documented.

Several studies have focused on sidestep cutting and the effects of fatigue, although research methods and subjects characteristics have differed (47, 48, 102, 112, 115, 117, 122). In summary the results of these studies have some similar theme. Fatigue produces more extended posture in the hip and knees at the same time as increased internal rotation in hip and knee is noticed (47, 48, 102, 112, 115, 117, 122). The frontal plane motion in the knee is often increased with fatigue, like peak knee abduction and knee abduction moment (47, 48, 102, 117). On the other hand in the studies Potter et al. (47) and Mc Govern et al. (48) had little different results with self-selecting cutting type. In their studies fatigue induced more extended posture in the hips and knees as others but the knees were more adducted post fatigue regardless of cut type. On the other hand knee abduction was greater in sidestep cut compared to crossover cut regardless of fatigue. Sidestep was chosen more frequently with fatigue. Majority of the studies are on females as they are of more interest regarding ACL injury risk factors. Regarding the fatigue protocols interesting results are that when comparing two different functional fatigue protocols both long (Slow Linear Oxidative Fatigue Protocol) and short (5 minute Agility Short-Term Fatigue Protocol) produced similar biomechanical changes (112). Additionally fatigue induced changes did not differ between the 50% and 100% fatigue levels in the study by Borotikar et al. (102). This was interpreted as the high risk changes in lower limb joint postures can occur at much lower level than often assumed. Finally some biomechanical fatigue effects like knee external abduction moment were still evident 20 and 40 minutes after fatigue in the study by Tsai et al. (117)

One group that is not so extensively studied in this context are pre-pubertal athletes. It is interesting to see if some sex difference exists before puberty and what the effect of fatigue is on that group. Furthermore if it is relevant to study this group regarding ACL injury risk, prevention methods and exercises.

1.7 Differences between the sexes in pubertal changes

It is a general consensus that pre-pubertal children and athletes usually don't display any significant sex differences in neuromuscular abilities like motor control (123), strength (123-125), coordination (125) or anatomical and hormonal variables (36). Minimal lower extremity biomechanical and neuromuscular differences are also thought to be between the sexes (36). Additionally there is no sex difference in injury rate in this population before the growth spurt (126, 127). About 60% of their injuries are joint sprains and majority of those occurring at the knee (127). During puberty, ACL injury rate in females starts to rise compared to men and concurrent sex differences in lower extremity biomechanics emerge during puberty with women showing riskier movement patterns for ACL injuries (127, 128). These findings suggest that boys and girls diverge from one another through the early pubertal transformation during the adolescent years following peak height velocity, which occurs at about 11-12 years in girls and 13-14 in boys (129, 130). Hormonal and anatomical differences are known but difficult to modify and address to prevent injuries. One year after peak height and weight velocities in males there is a marked acceleration in strength gain compared to females, this gain is much smaller in females and they often show sign of increased subcutaneous fat compared to increased lean muscle mass in males (128, 129). Simultaneously with these changes, power or strength and coordination increases in males compared with that seen in females. This is particularly evident in tasks affected by strength and lean body mass like throwing, long jump and running (131, 132).

Research assessing movement strategies across various stages of maturation have mainly focused on double limb task. They have demonstrated difference between pubertal and pre-pubertal females but not between pre-pubertal and pubertal males, these differences include greater knee valgus angles, knee adductor moments and smaller knee flexion angles during double-limb landing tasks in pubertal and post-pubertal females (130, 133, 134). On the other hand differences have been noted between prepubescent boys and adult men in DJ where men had higher performance and more efficient performance both regarding kinematics, VGRFs and, muscle activation and stiffness, of the lower extremity (135). These studies support the consensus that the sexes diverge from one another following maturation and girls use movement strategies that are more likely to cause ACL injuries.

One limitation of researches assessing movement strategies across various stages of maturation is that they have mainly looked at double limb task. This is relevant as the ACL injury predominantly occurs during deceleration, cutting or 1-legged landing maneuvers associated with high external knee joint loads (12, 13). Although some sex differences have been established during single leg maneuvers it is of questionable clinical relevance (53). On the other end, the pre-pubertal situation is not as well established or how maturation influences the performance of such task. Sigward et al. (128) investigated this with the purpose to determine whether there were biomechanical differences of the lower extremities between male and female soccer athletes during 45° sidestep cutting maneuver, across different stages of maturational development. Participants were between the ages of 9 and 23 years. The results were that no sex-maturation interaction were found for any variable. On average, females exhibited greater knee abduction and adduction moments than males. When collapsed across maturation groups, females exhibited 20% higher knee adductor moments and nearly twice the amount of knee valgus when compared with males. Pre-pubertal athletes demonstrated greater knee adductor moments and GRF´s than all other groups. The conclusion was that less mature athletes exhibit riskier biomechanical pattern for injury during cutting than the mature ones. In contradiction to other studies this study did not support the hypothesis that sex differences would only emerge after puberty and the largest sex difference was evident in the pre-pubertal athletes.

This discrepancy between single and double limb tasks could be related to task demand. Children, 9-11 years old, seem to use less efficient steering and reorientation strategies when negotiating around environmental obstacles and have more difficulty performing higher precision locomotor tasks (136, 137). Cutting could be an additional challenge to younger athletes and when cued at random like in the study of Sigward et al. (128), even more so as they have not fully developed their perceptual motor processes. When considering the effects of fatigue, there is no study that has looked at the effects of fatigue on sidestep cutting performance in pre-pubertal athletes or the effects of maturation and sex in that context. Another factor to look at in this perspective is the timing of the maturation neuromuscular training and preventive method, with the intension to reduce the likelihood of non-contact injuries. Whether neuromuscular training is too complex for the pre-pubertal population, also needs to be considered.

1.8 Implementation of neuromuscular training and reduction of ACL injury incidence

In a Meta-analysis done by Myer et al. in 2013 (126), the purpose was to examine the effect of age of neuromuscular training (NMT) implementation on the effectiveness for reduction of ACL injury incidence. They concluded that both biomechanical data and the current epidemiological data indicate that the best prophylactic effect for prevention exercises for optimal ACL injury risk reduction is during pre- or early adolescence before the period of altered mechanics that increase injury risk and before peak injury incidence. This was demonstrated by dichotomized analysis that established 72% risk reduction for pre or early adolescence athletes compared to 16% in over 18 years old.

Myer et al. (126) also concluded, based on their data, that the most effective and efficient youth injury prevention programs appear to require the combination of components including, plyometric, dynamic stabilization, strength, and feedback driven technique training and the effects of these components are potentially additive when employed during both the pre and post season. Besides, to address the neuromuscular control of the lower extremity and to maintain proper landing mechanics, increased emphasis has been on the link to hip abductors and trunk stability in this context (126). The theory is that there will be increased ability to maintain proper landing mechanics though increasing hip strength and decreased lateral trunk motion by improving the control of the core musculature. This strengthens the motive to study better sidestep cutting movement in pre-pubertal athletes. This includes examining if differences in biomechanical and neuromuscular factors exist between the sexes for this movement. Additionally this includes looking at the effects of NMT starting in the pre-pubertal population on ACL injury risk and incidence.

2 Aims

Certain kinetic and kinematic variables have been identified as risk factors for ACL injuries and been studied extensively in post-pubertal athletes of both sexes. It is well established that the injury predominantly occurs during deceleration, cutting or 1-legged landing maneuvers associated with high external knee joint loads. Effect of fatigue on neuromuscular control has been shown to be different between the mature sexes and it potentially results in increased frequency of injuries in females. Research on effects of sex and maturation in sidestep cutting are scarce. When adding the variable of fatigue there are no studies in the pre-pubertal athlete's population.

The aim of this cross-sectional study was to identify biomechanical differences among 10-12 years old boys and girls during sidestep cutting maneuvers and effect of fatigue and side. This was done by evaluating sex differences for frontal plane trunk and knee angles and frontal plane knee moments the first 50% of the stance phase (50% SP) of a sidestep cutting maneuver and the effects of fatigue and side on performance. Secondly the effects of sex, fatigue and side on the horizontal GRF during the landing phase. Finally the effects of lateral trunk motion on frontal knee moments and influence of sex, fatigue and side during the same phase were evaluated. The focus on the acceptance part of the early stance phase is relevant due to the increased ACL injury risk during that phase (13).

Research questions are:

- Are there any differences presented in the horizontal GRF, Trunk lateral flexion and/or knee joint kinematics in the frontal planes between boys and girls during the 50% SP of sidestep cutting maneuver?
- Does fatigue have an effect on the horizontal GRF, Trunk lateral flexion and/or knee joint kinematics in the frontal planes in boys and girls during the 50% SP of sidestep cutting maneuver?
- Does the lateral trunk motion affect the frontal knee moments during the 50% SP of sidestep cutting maneuver. Is there influence of sex and fatigue on that relationship?
- Does side have any effect on the horizontal GRF, Trunk lateral flexion and/or knee joint kinematics in the frontal planes in boys and girls during the first 50% of the landing phase of sidestep cutting maneuver?

Research hypotheses

1. Boys and girls will demonstrate similar movement patterns, both pre- and post- fatigue
2. Fatigue increases peak horizontal GRF in both sexes
3. Fatigue increases lateral trunk flexion at IC and increases its excursion
4. Fatigue increases knee abduction at IC and increases its excursion
5. Fatigue increases peak knee abduction moment during the landing phase
6. The main effect of side does influence the movement pattern of trunk and knee
7. Lateral trunk movement will affect knee frontal plane moment

3 Methods

3.1 Research design

This is a cross sectional study that included two groups, 1) 10-12 year old boys 2) 10-12 year old girls. The study protocol was approved by the review board at the National Bioethics Committee (VSNb20112020011/03.7) and announced to the Icelandic Data Protection Authority.

3.2 Participants

Participants were team handball or soccer players recruited during 2012-2014 from local athletic clubs, with the collaborative efforts of staff and coaches during the research period (Appendix I). This included contacting the participants' parents or guardians and provide written information from the researchers explaining in simple terms: the purpose of the research and the procedure involved the participants' right to withdraw at any time without a penalty of any sort, potential benefits, potential risk and assurance of anonymity (Appendix II). Subsequently, researchers contacted each parent or guardian to see if they were willing to let their children participate.

Criteria for exclusion were history of torn knee ligaments or muscles of the lower extremities, intra-articular corticosteroids injections within the previous three months, neurological impairments, impaired balance and any orthopedic problems of the lower limb. If the potential participant met the criteria, had parental approval and was interested in taking part in the study, an appointment was made for testing session. Prior to testing session, all participants (and their guardians since participants were younger than 18 years old) signed an informed consent form approved by the Icelandic Bioethics Committee that review the information just described (Appendix III).

3.3 Procedure overview

All testing was conducted at the Research Centre of Movement Science, Department of Physical Therapy, Faculty of Medicine, School of Health Science, University of Iceland, Reykjavík, Iceland. The study period was from January 2012 to February 2014. In short, the measurement session started with participant putting on appropriate athletic clothing (tight shorts, sneakers and tight top for the girls), after which height and weight was measured, followed by a 5 minute warm up on a stationary bike (Keiser Power Pacer). The children were instructed to bike at moderate intensity just like they were warming up, that is getting warmer and the breathing a bit higher but without strenuous effort. After the warmup, maximal voluntary isometric contraction of hip- abduction and external rotation was conducted. This will not be addressed further here since the data are not used in this thesis. The next procedure was to secure reflective markers on the skin of the subjects for biomechanical measurements. They were placed on by an experienced physical therapist, according to C-motion marker set placement guidelines (C-motion,Germantown,USA) https://www.cmotion.com/v3dwiki/index.php/Marker_Set_Guidelines (Appendix IV) , Figure 1 and Figure 2. These markers were used to define joint centers and track the segments of the trunk, pelvis and lower extremities. Clusters of 4-5 markers were used to track each defined segment during dynamic trials. They were secured with Velcro and straps or kinesio tape to avoid movement of the clusters of markers. Biomechanical data were then captured using a 3D motion capture system during five successful trials of DJ and sidestep cutting maneuvers both to the left and right. After this a fatigue protocol was executed followed by another set of DJ and sidestep cutting. The order of sidesteps and DJ were in random order between subjects. The details of the fatigue protocol and motion analysis are described below. The DJ will be excluded as it is not used in this report.

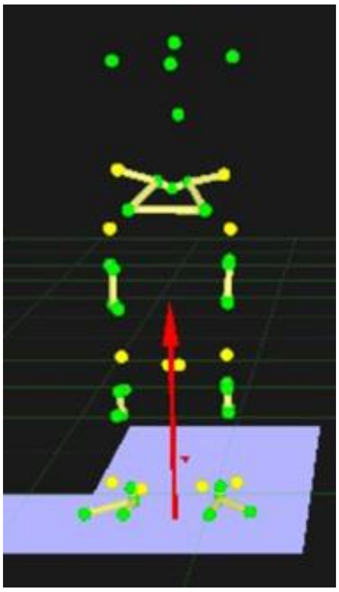

Figure 1 Frontal view of marker placement. Standing calibration from QTM (Qualisys Track manager)

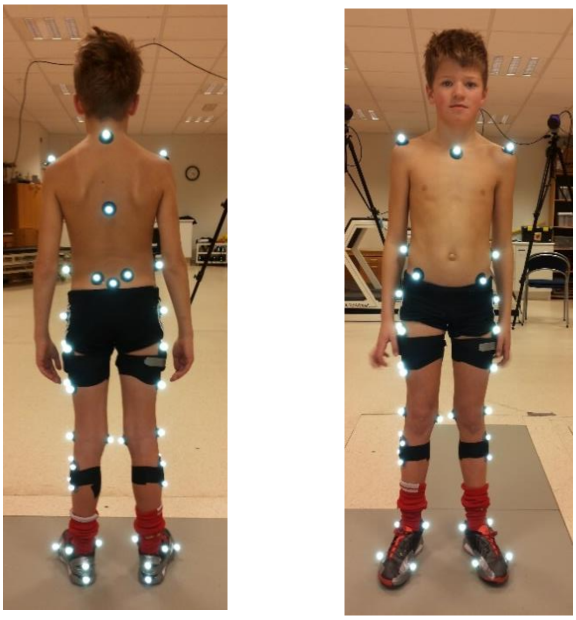

Figure 2a) and b) Motion analysis lab at the Research Centre of Movement Science. Back and frontal view of marker placement

3.4 Fatigue protocol

To fatigue the participant a slide board was used. The rationale behind this was to fatigue the lower extremity and especially the hip abductors and external rotators and lateral flexors of trunk, in addition to the lower limb extensors. The slide board was approximately 2 meters long and 0.6 meters wide (Figure 3). The surface of the board was slippery and polished regularly to keep it that way. Bumpers were located at each end of the board and the length between them was adjusted to the formula 1,5x the subjects leg length. Before the procedure the reflective markers on the sides of the shoes were screwed off and slippery material put around the shoes. The participants were asked to maintain a semi-squat position and to push of the bumpers with the lateral foot and glide to the other side. This movement was repeated back and forth for a total of 5 minutes. The intensity of the movement was increased every minute and for the last minute it was an all-out effort. Participants were then asked to rate their fatigue level on a 0-10 numerical rating scale (NRS) where 0 implied no exertion and 10 indicating maximal fatigue.

Figure 3 Motion analysis lab at the Research center of Movement Sciences, fatigue protocol set up. Diagonal view of slide board (2mx0.6m), push off from side to side.

3.5 Motion analysis

Biomechanical measurements

An eight camera Qulisysis Oqus 300 motion capture system (Qualysis AB, Gothenburg, Sweden) was synchronized to two force platforms (AMTI) in to the lab floor. Qualysis track manager software simultaneously recorded motion and force plate data, with the sampling rate set at 200 Hz. An initial static trial was recorded and the data used to determine body mass and relative marker orientation, and in order to define segments and their local reference systems as well as joint centers for the model. Both static and dynamic measurements were captured within a pre-calibrated area. Data were exported as c3d files and Visual3D software (Visual 3D^{TM} C-motion, Germantown, USA) used to calculate joint angles and moments from dynamic trials. During performance of the sidestep cutting maneuver, the subjects cut at a self-selected angle with the goal of passing by a static 'defender' made of a tripod stand with a drawing of a face at the top. The participants were asked to take a step onto the force plate and try to fake in one direction and cut to the other as quickly as they could (see Figure 5 and Figure 4). A trial was considered successful where the foot landed on the force plate and the cut was in the right direction.

The outcome variables under investigation during performance of sidestep cutting maneuver are:

a) The horizontal GRF
b) Frontal plane trunk and knee angles at IC
c) Frontal plane trunk and knee excursion during the 50% SP
d) Peak external frontal plane knee moments during the 50% SP. Positive value represents valgus.

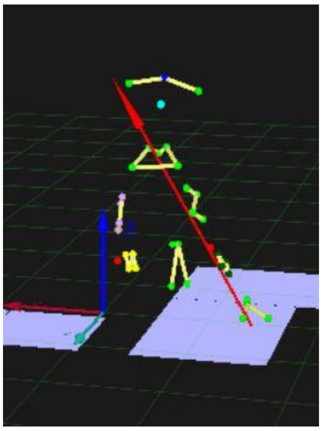

Figure 5 Motion analysis lab at the Research Centre of Movement Science. Sidestep cutting maneuverer passing static "defender" made of tripod stand.

Figure 4 Motion analysis lab at the Research Centre of Movement Sciences. Sidestep cutting on force plate. Resultant force vector and retro-reflective markers visible.

Data managing and processing

Commercial software (Visual 3D^{TM} C-motion, Germantown, USA) was used to process the raw motion and force plate data prior to outcome calculations. Marker and GRF data were low pass filtered with a Butterworth filter with a cut-off frequency at 6 and 15 Hz, respectively. After defining the segments of the model, as per the static trial the template was applied to the dynamic trials and rotations between segments were calculated and joint moments derived. Stance time was identified from force plate data (from toe on to toe off), force and kinematic data normalized to 101 data points and an ensemble average was derived across at least three trials for each condition (pre- and post-fatigue). Data were then exported from Visual 3D to Microsoft excel and it along SAS Enterprise Guide 7.1 statistical software used for further analysis.

3.6 Statistical data analysis

Mixed model analysis was used to statistically analyze force plate and kinematic data per limb, pre and post fatigue (within subjects' data) and compared between sexes. Post-hoc testing was conducted where appropriate. Independent-t tests were used to compare male and female demographic data. Pearson Product Moment Correlation Coefficients were used to evaluate association between knee moment and trunk angles. Alpha was set at 0.05.

4 Results

4.1 Participants demographics

No statistical differences were found between the sexes for mean age, height, weight, Body Mass Index (BMI) or the NRS of fatigue (Table 1).While 97.4% of females indicated right leg dominance, 90.2% of the males did

Table 1. Mean (SD) for participants; age, height, weight and BMI (Body Mass Index) and fatigue rating (Numerical Rating Scale (NRS)) after a fatigue protocol.

	Female N=76		***Male N=52***			
	Mean	SD	Mean	SD	Min	Max
Age (years)	10.63	0.66	10.54	0.79	9	12
Weight (kg)	41.21	9.43	41.12	7.95	27.80	79.30
Height (cm)	148.6	8.5	149.9	8.1	132.0	180.6
BMI	18.52	2.99	18.06	2.20	13.59	30.17
NRS	6.79	1.80	7.29	1.84	1	10

4.2 Force Plate data- horizontal GRF (X)

The peak horizontal medial-lateral ground reaction force (ML-GRF) within the 50% SP was identified before and after the fatigue protocol. The only significant effect identified during the sidestep cutting was the one of fatigue ($p<0.001$; see Figure 6). No significant effect was found for limb or sex, although the difference between the 8.23 N/kg in males versus 7.76 N/kg in females was near significance ($p=0.067$). No significant interaction was found between variables.

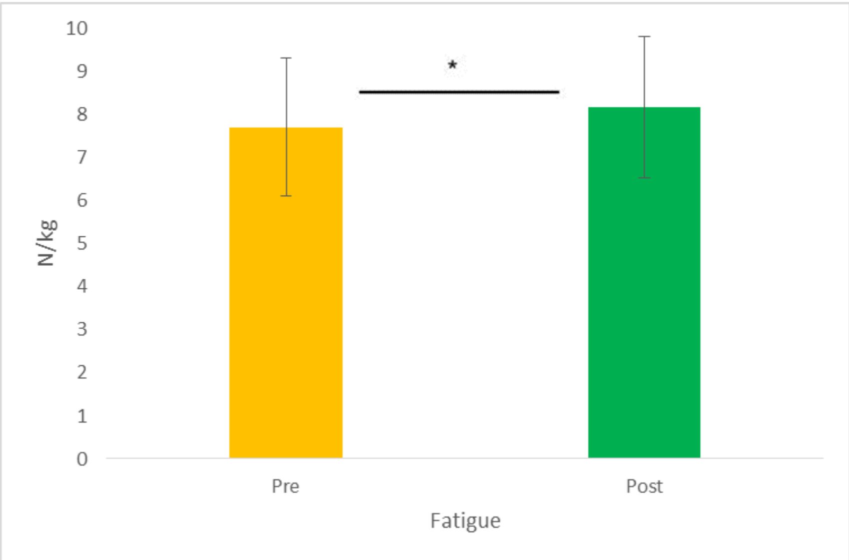

Figure 6 Mean (SD) maximal normalized horizontal (X) GRF (N/Kg), during 50% SP, before (pre) and after (post) the fatigue protocol. *Significant increase from pre-fatigue values p<0.001.

The size and direction of the resultant GRF (x-y-z) in frontal plane and the sway of the trunk and movement of the lower extremity of one individual is demonstrated in Figure 7 a - c. These figures show the position of the body and the force approximately from 20-40 ms after IC or first 8-24% of the SP. In Figure 7a the resultant force falls outside the knee and represents an external valgus moment at the knee. On the other hand in Figure 7b and 7c the opposite is seen this is not the case. The size and timing of normalized ML-GRF (N/kg) of duration from IC to toe-off of one individual is demonstrated in

Figure 8. The SP is normalized to 101 data points.

7 a. 7 b. 7 c.

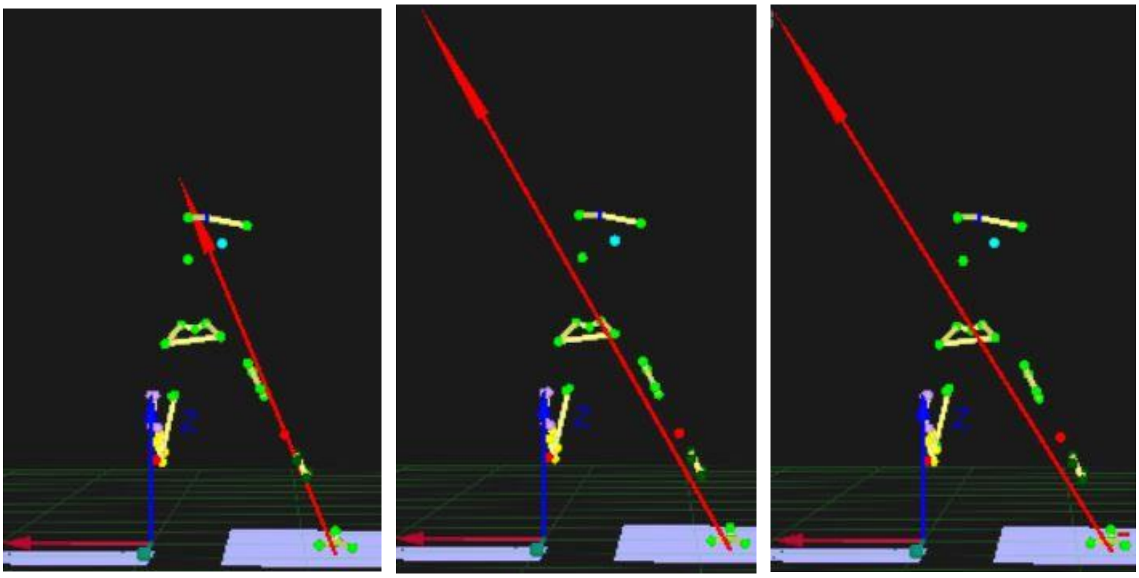

Figure 7 a-c. These figures show the sidestep cutting and the GRF vector in frontal view of one subject. 7a: approximately 20 ms after IC; 7b: 30 ms after IC; and 7c: 40 ms after IC or 8-24% of the SP. The red dot represents the lateral knee marker.

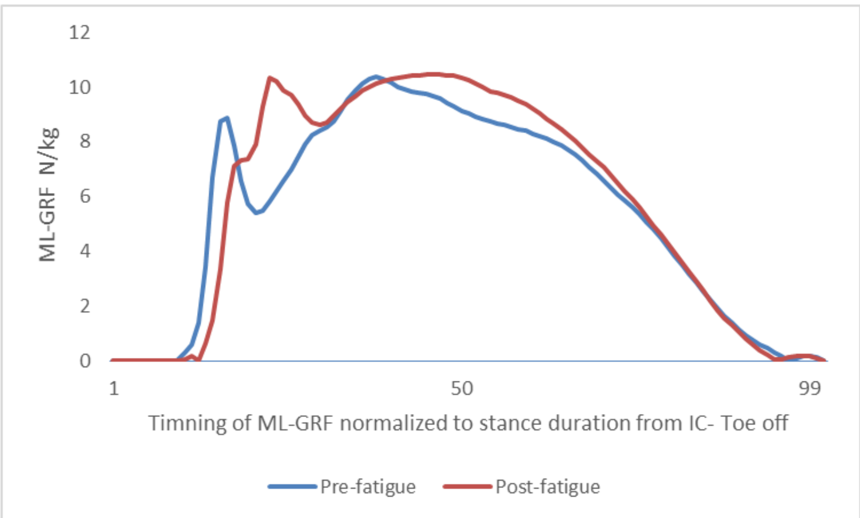

Figure 8 The mean ML-GRF from IC to toe-off for pre and post fatigue of one individual.

4.3 Frontal plane trunk angle

At IC, a significant main effect was found due to a difference between sides and slight effect of fatigue was also found. The mean measurement of ipsilateral lateral flexion at IC was 1.6° on the right side versus 3.5° on the left (P<0.001). The mean pre fatigue measurement at IC was 2.1° versus 3.0° post fatigue (p=0.049). No main effect of sex was found and no interaction between the variables. For the maximal angle within 50% SP, the only significant main effect was side (p<0.001). The ipsilateral lateral flexion was 10.3° on the right side versus 13.5° on the left. Similarly, a main effect for side was found for frontal plane trunk excursion during the first 50% of stance (p<0.001) with 8.7° on the right versus 10.1 on the left, (Figure 9). In addition there was a significant main effect of fatigue (p=0.006) with 9.9° excursion pre-fatigue versus 8.9° post-fatigue (Figure 10). No main effect of sex was found for the excursion and no significant interaction between variables.

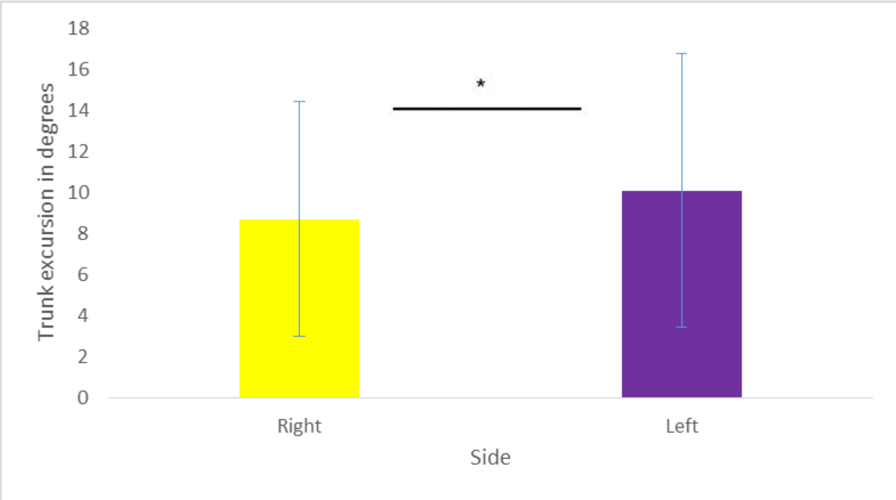

Figure 9. Degrees of ipsilateral trunk excursion during 50% SP of during sidestep cutting. Difference between right and left side.

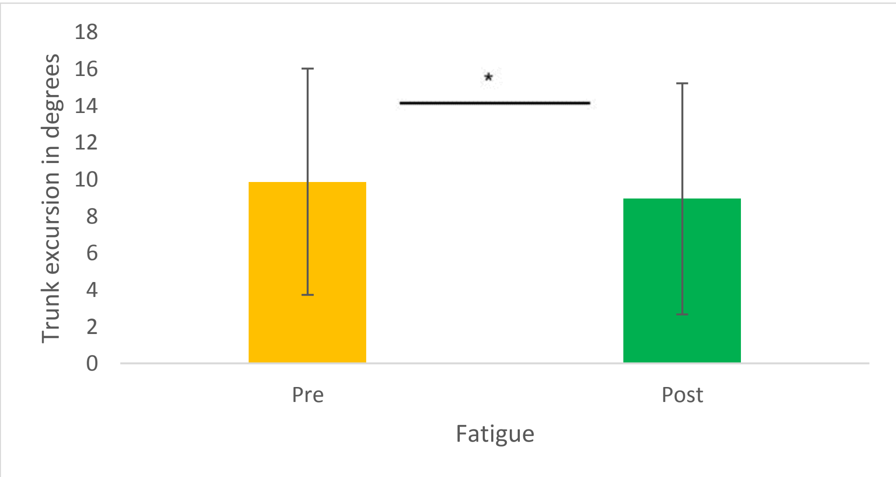

Figure 10. Degrees of ipsilateral trunk excursion during 50% SP of during sidestep cutting, before (pre) and after (post) fatigue.

4.4 Frontal plane knee angle

For the frontal plane knee angle at IC, there was a significant main effect of fatigue as the knees were in 0.1° abduction pre-fatigue versus 1.0° post fatigue (p=0.019; Table 2). There was also a significant main effect of side with the right being in 1.0° versus 0.1° abduction on the left (p=0.008; Table 2). There was no significant difference between sexes (Table 2). The same was evident for the maximal abduction values during the 50% SP. There was a significant main effect of fatigue as the knees were in 5.6° abduction pre- versus 7.6° post-fatigue (p <0.001). There was also a significant main effect of side with the right reaching a maximum of 7.7° versus 5.5°on the left (p <0.001). The interaction of side-fatigue was significant (p=0.011) as fatigue had a relatively greater effect towards increased abduction on the right compared to the left side (Figure 11). For the knee valgus excursion during the first 50% of SP there was a significant main effect of fatigue (p<0.001) due to a mean difference of 1.1° between pre- and post-fatigue values. There was also a main effect of limb, due to greater excursion on the right by 1.4° (p<0.001). Thirdly there was a significant main effect of sex (p=0.018) with the boys moving 5.4° into valgus versus 6.5° by the girls (Table 2). Two significant interactions were found, that of side-fatigue due to more post-fatigue excursion on the right side (p=0.018) and fatigue-sex due to greater post-fatigue excursion of females (p=0.025), Figure 12.

Table 2. Knee abduction at IC (initial contact) and max angle during 50% SP and the excursion between. * Significant difference between right and left sides and pre and post fatigue and excursion between male and female

Knee Abduction	IC	Max angle 50%	Excursion
Right	0.99°	7.70°	6.71°
Left	0.11°	5.45°	6.29°
Significance	*p=0.008	*p <.0001	*p<0.001
Pre	0.13°	5.60°	5.47°
Post	0.98°	7.57°	6.59°
Significance	*p=0.019	*p <.0001	*p<0.001
Male	0.51°	5.88°	5.36°
Female	0.58°	7.10°	6.48°
Significance	p=0.940	p=0.170	*p=0.018

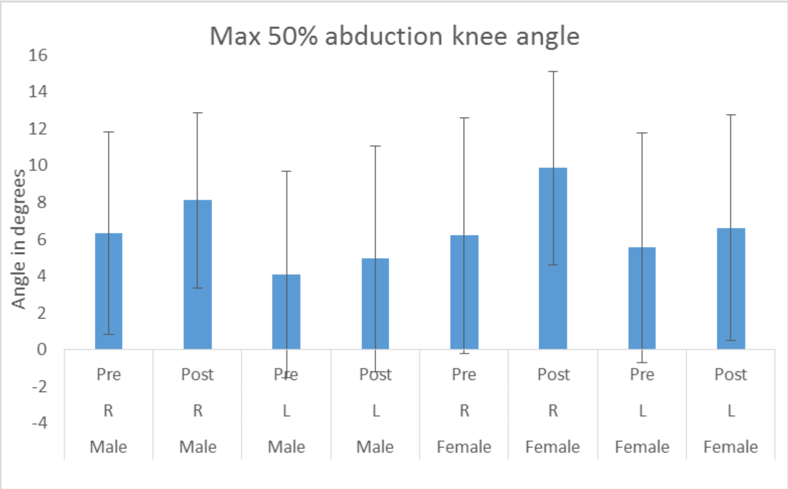

Figure 11. Maximum knee angle during 50% SP for the right (R) and left (L) side of males and females, before (pre) and after (post) fatigue. Side-fatigue interaction: p=0.011.

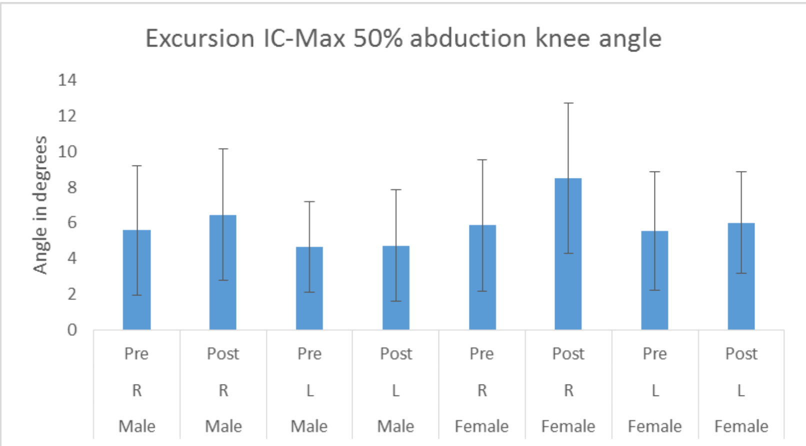

Figure 12. Knee abduction excursion (degrees) for right (R) and left (L) side of males and females, before (pre) and after (fatigue). Side-fatigue interaction: p=0.018, fatigue-sex interaction: p=0.025.

4.5 Knee frontal plane moment

There were two significant main effect for the frontal plane knee plane moment. The other was sex demonstrated with greater external knee valgus moments in males during the 50% SP of sidestep cutting compared to females, (p<0.001;Figure 13). This moment demonstrates the first peak occurring early in the stance phase. The timing of the ML-GRF in respect to the timing of the knee moment in frontal plane for an individual measurement is shown in Figure 14 and the ML-GRF timing in respect to the knee angle excursion in frontal plane for an individual measurement is shown in Figure 15. No difference was observed in peak varus knee moment during 50%SP between the sexes (p=0.827) and no main effect of fatigue (p=0.139). However, there was a significantly greater varus peak on the left side compared to the right side (0.20 Nm/kg vs 0.18 Nm/kg; p=0.022).

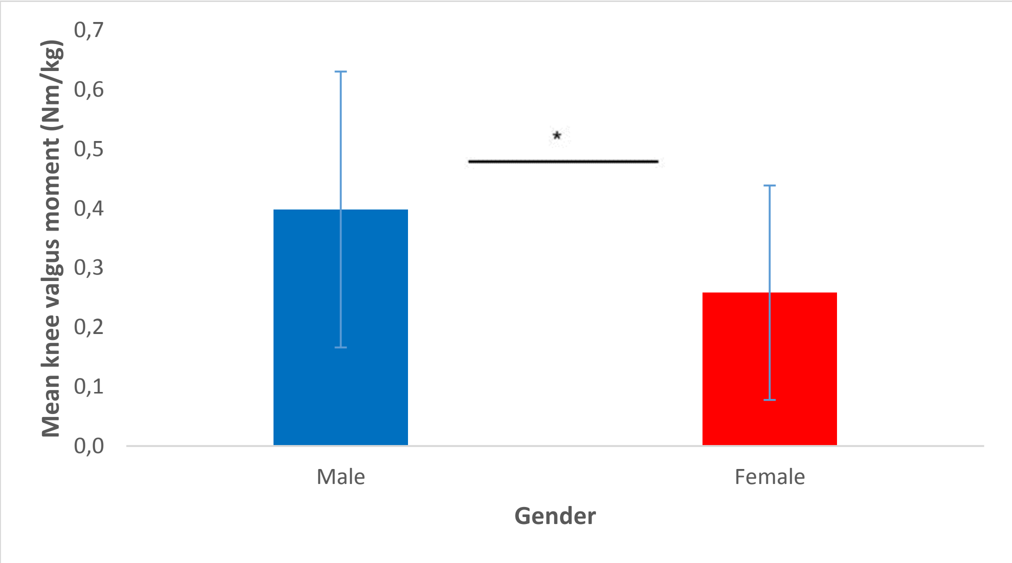

Figure 13. Mean maximum valgus knee moment during the 50% SP during sidestep cutting.

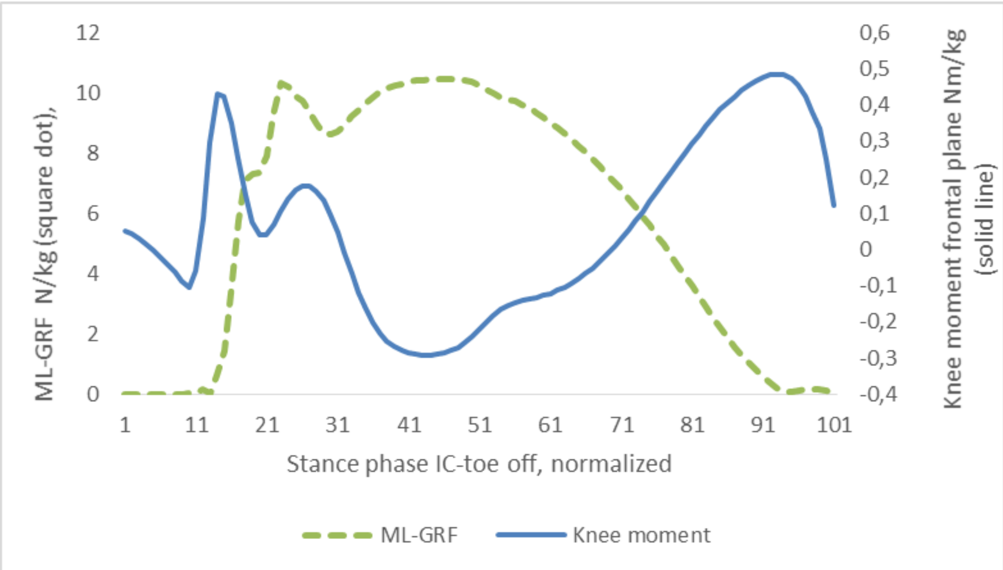

Figure 14. The relationship and timing of outcome measures of a single individual during sidestep (post fatigue) for the left side. Positive value of the knee moment represent valgus. The stance is normalized, from IC to toe-off.

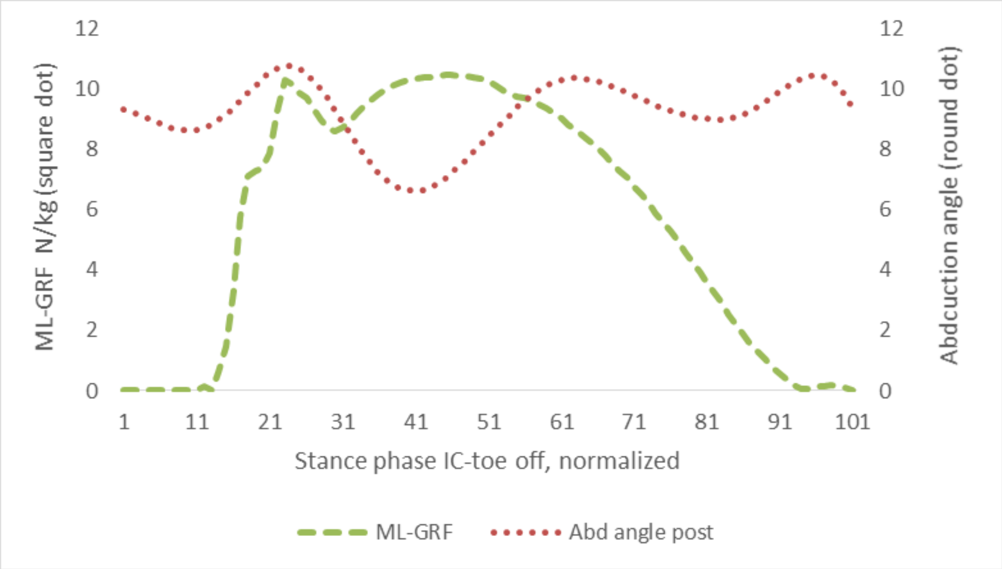

Figure 15 The relationship and timing of outcome measures of a single individual during sidestep (post fatigue) for the left side. The stance is normalized, from IC to toe-off.

4.6 Correlations

Regression analysis did not show any correlation between peak valgus moments during the 50% SP and trunk lateral flexion at IC or between or peak varus knee moment during the 50% SP and maximal trunk lateral flexion during the same time frame see Table 3. Regression analysis during the 50% SP. The timing of knee frontal plane moment with respect to the timing of knee and trunk angle excursion in the frontal plane is shown in Figure 16 where the average for one individual during post-fatigue sidestep on the left side is represented. Similar data representing the average for the whole cohort post fatigue measurement for the right side stance phase is in Figure 17.

Table 3. Regression analysis during the 50% SP.

Regression analysis	Max trunk lateral flexion	Trunk lateral flexion at IC
Max (valgus) knee moment 50% SP		r= 0.083; p= 0.060
Min (varus) knee moment 50% SP	r= 0.037; p= 0.791	

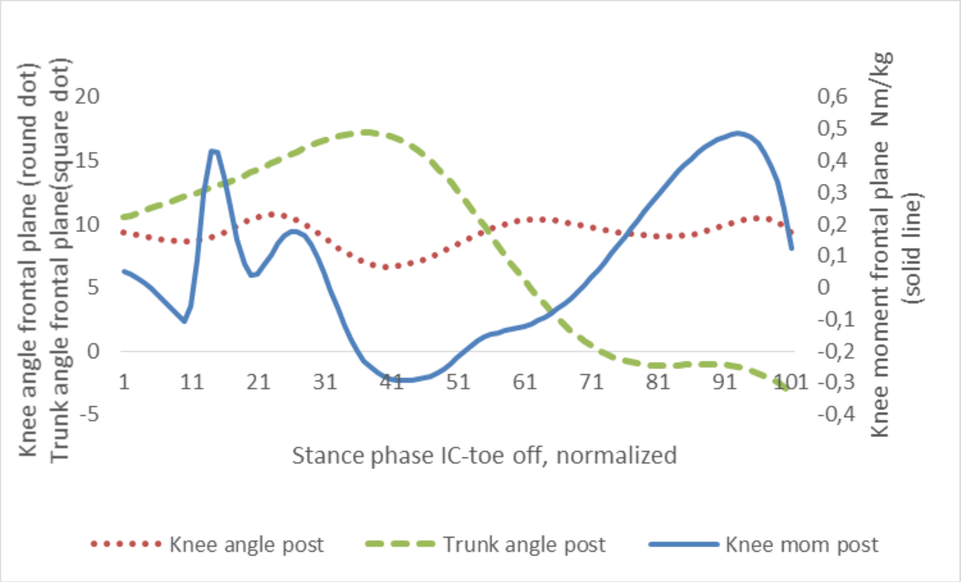

Figure 16 Data representing an individual average measurement during sidestep post fatigue for the left side. The frontal plane knee moment is scaled on the right (valgus (positive) and varus (negative)) with respect to ipsilateral frontal plane trunk lean and knee abduction angles on the left. The stance is normalized, from IC to toe off.

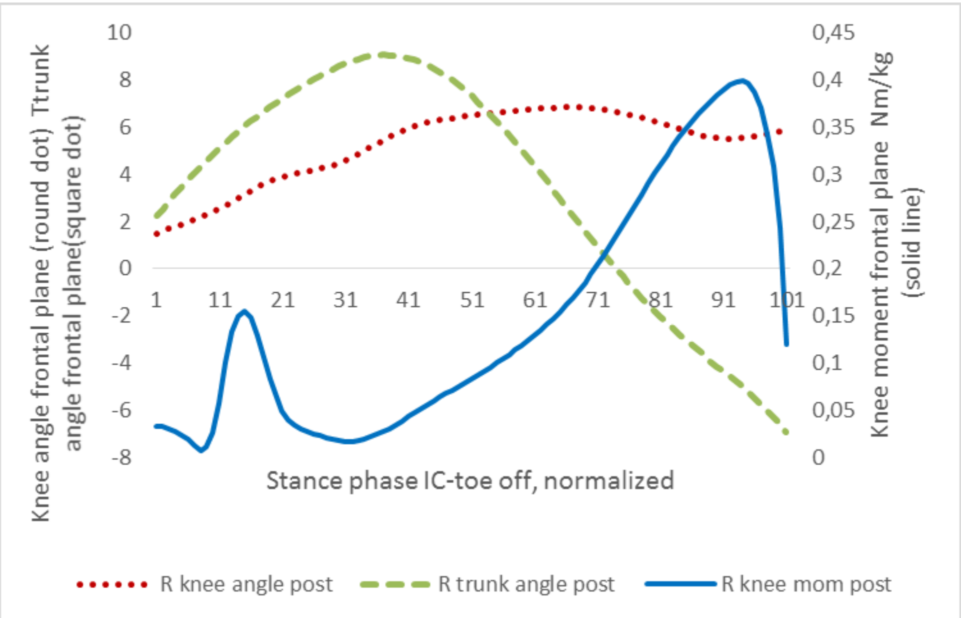

Figure 17 Data representing the average for the whole cohort post fatigue measurement for sidestep on the right side. The timing of knee frontal plane moment with respect to the timing of knee excursion in frontal plane and knee excursion. The frontal plane knee moment is scaled on the right (valgus (positive)) with respect to ipsilateral frontal plane trunk lean and knee abduction angles on the left. The stance is normalized, from IC to toe-off. R=right.

5 Discussion

The main results of the study does not unanimously support the hypothesis that boys and girls demonstrate both pre- and post-fatigue, similar movement patterns. There are two major exceptions to this hypothesis: a) boys demonstrated a greater peak knee valgus moment than girls during the early stance phase and; b) the knee abduction excursion was greater in girls than in boys during sidestep-cutting. This suggests that sex-dependent differences in movement patterns may already exist before puberty. Furthermore, the results support the hypothesis that fatigue increases peak horizontal GRF in both sexes. The hypothesis that fatigue would increase maximal ipsilateral lateral trunk flexion at IC was supported but not the hypothesis that the excursion of the same movement would increase. The hypothesis that fatigue would increase knee abduction at IC and increase its excursion was supported, although fatigue did not significantly increase the peak knee abduction moment. Furthermore, no relationship was found between frontal plane knee moments and ipsilateral lateral flexion of the trunk.

5.1 Horizontal GRF (X)

Effect of sex

The hypothesis of no sex-dependent difference regarding the peak ML-GRF was supported. Nonetheless, a trend was seen for greater ML-GRF in males (8.23 N/kg) vs. females (7.76 N/kg; p= 0.06). This is in line with significantly higher valgus moment in males compared to females in our study. Sigward et al. (128) did not find significant difference for GRF (veritcal, posterior, lateral) across maturation. On the other hand, the comparison is difficult as here the maximum GRF for the 50% SP is used whereas many others have used the first peak of the weight acceptance (128, 138).

The GRF presents an important component of external loading experienced by the human body and the musculoskeletal system at contact with the ground. Studies have measured this force 2-11 times the bodyweight in running and DJ (139). In this regard, it is clear that athletes need to actively manage the collision with the ground and dissipate the forces to minimize possible adverse effects. Active management of the collision is thought to be done through adjustment of body stiffness and regulation of joint rotation, which requires constant use of muscle force. It is well established that the muscles are activated both for preparatory means prior to landing and after landing in response to the impact (140), corresponding to the preparatory feedforward muscle and joint action and the subsequent muscle action and the feedback response to the impact, respectively (141).

The ground reaction vector is three dimensional and both the vertical and horizontal components often have two peaks. The first results from collision with the ground while the second is of a lower frequency and is more influenced by neuromuscular feedback (141). Due to the nature of the task the horizontal component is of course much higher and more relevant in sidestep than in tasks that don’t involve such dynamic change in direction (72, 139).

There are limited number of studies that have investigated the direct relationship of the GRF and loading rate (LR) with injuries. According to Zadpoor et al. (139), higher values of these variables are often presumed to increase landing or running injuries, but the literature is equivocal about the validity of this assumption. On the other hand a systematic review by Zadpoor et al. (142) concluded that only increased LR of the GRF was related to lower-extremity stress fracture. Also, in the prospective study of Hewett et al. (35), ACL injured females had 20% higher peak VGRF and 16% shorter contact time before injury compared to the non-injured ones. The study by Iguchi et al. (118) is the only one that specifically has looked at unanticipated sidestep cutting and the effects of sex and fatigue on GRF. The outcome was that women demonstrated significantly larger impulse of the VGRF during the first 50 ms than men after fatigue. The sex difference for ML-GRF could relate to the approach speed but this was not measured in the current study. On the other hand, there was a great variety in the execution, speed and technique which mirrors the notion that this is a complex task that has not been mastered by most of the immature and pre-pubertal athletes (136, 137).

Effect of fatigue

The hypothesis of increased peak horizontal ML-GRF within the 50% SP after fatigue in both sexes was supported. The altered control of this collision with the ground due to fatigue is thought to, at least partly, contribute to ACL injury by increasing the load on passive structures. Inspired from this, researchers have studied the relations between fatigue and loading of the musculoskeletal system as represented by the characteristics of the GRF.

Fatigue induced changes in GRF magnitudes during the impact and eccentric phase of locomotor activities reflect alterations in segmental control that may alter the load on passive structures (141). However, research has demonstrated contradictory direction of change in GRF magnitudes during fatigued locomotion, as some researchers have found no significant change (143, 144) while others have either observed increase (118, 145, 146) or decrease with fatigue (101, 120, 147). The effect of the nature of fatigue protocol and to what extent it affects the changes in the GRF or LR is not clear (139).

The first line of reasoning speculates that the ability of the human body in managing the collision with the ground decreases with muscle fatigue and therefore the GRF or LR increases. Increase of impact peak may be explained by increased pre-activation of the stabilizing musculature that may result in increased joint or system stiffness and subsequent reduced shock absorption (106, 139, 141). The second line of reasoning speculates that body has a protective strategy that lowers the GRF or the LR to protect the body from possible injuries. Decrease of the peak GRF values has been suggested to be a consequence of altered stretch reflexes (139, 141) or greater flexion angles at impact during landing (139).

One interesting aspect of this is based on the results of James et al. (141) which indicate that events that are controlled by pre-planned feed-forward mechanisms may induce increased magnitudes of the GRF during fatigued landing, due to increase in EMG pre activity and thereby possibly in lower extremity joint extension (corresponding to GRF first peak). On the other hand, GRF events controlled by feedback mechanisms may decrease during fatigued landings, possibly as a result of decreased stiffness in the presence of diminishing force production ability of the involved motor units or changes in tissue compliance (corresponding to GRF second peak). Decreased knee flexion at IC may be a part of an adaption to reduce the muscular demand imposed by the external moments (139, 141).

Even though the direction of sidestep cutting in this study was pre-planned and the speed not controlled for, the protocol induced sufficient fatigue to cause higher ML-GRF that corresponds to the second peak of the force. The average fatigue-rating of the subjects was around 7 on NRS which should have been enough to produce fatigue induced changes (102). The results relating to GRF data may represent a less efficient motor strategy and the so-called ligament dominance as introduced by Hewett et al. (21), where the muscles do not sufficiently absorb the GRF and the joint and ligaments must absorb the force, resulting in high force or impulse over brief period of time which could result in ligament rupture. The size of the ML-GRF is somewhat lower than seen in other studies (72) which may render the effects of fatigue on forces, angles and moments relatively smaller, as higher forces have potentially larger effects on the body.

5.2 Frontal plane trunk angle

Effect of sex

There was no main effect of sex for the movement of trunk in the frontal plane which was in line with our hypothesis regarding no sex-difference. In other words the 10-12 year old girls and boys chose similar movement strategy for the trunk in the frontal plane during sidestep cutting.

Effect of fatigue

Fatigue induced significant changes as hypothesized. This was evident by the children positioning their trunk into more ipsilateral trunk flexion at IC, that is, more toward the planted foot. On the other hand, there was significantly less excursion into ipsilateral trunk flexion post fatigue during the 50% SP, while lateral flexion increased at IC and maximum angles did not change between pre and post fatigue. It was not possible to compare these results of the effects of fatigue to other research as there were no similar studies found in any population.

It is tempting to suggest that increased lateral trunk position toward the planted foot as seen at IC in the fatigued state is a riskier pattern than that demonstrated during the pre-fatigued state. This is based on the notion that both the first peak of the GRF and frontal plane knee moment occur at the beginning of the weight acceptance phase, 20-40 ms into the phase, in the same time frame ACL injury is expected to occur (69, 72, 139, 141). Trunk lean (peak outside tilt) has been associated with peak knee abduction moment (78, 80) and increased lateral displacement of the trunk has been found to be a predictor for knee ligament injury (40). This effect is expected because deviation of the torso from vertical may cause the GRF to pass more lateral with respect to the knee, thereby increasing its moment arm and resulting knee abduction moment. The total excursion after fatigue was decreased. It can be argued based on the literature that the total motion during stance phase in frontal plane is probably not the key factor related to injury, but rather the position at IC and how fast the trunk moves into the contralateral motion during the first phase of weight acceptance, as this is the most vulnerable time regarding injury risk.

Effect of side

The hypothesis that side would significantly affect trunk motion was supported, but no interactions of sex or fatigue related to side were found. The trunk was more laterally flexed toward the left compared to right stance leg at IC and the maximum angle and excursion were also larger in the same direction. This could potentially increase the abduction moment and therefore ACL injury risk (40, 78, 148). In support of that assumption are findings that indicate more ACL injuries may occur on the non-dominant leg (74).

5.3 Frontal plane knee angle

Effect of sex

A significant sex-difference for the excursion in the frontal plane is not entirely in line with the hypothesis in this study and general consensus of the similar movement pattern between the pre-pubertal sexes. The sexes are at the same angle at IC but the females move significantly more into abduction during the first half of the stance phase. On the other hand there is a question of clinical relevance as the difference is only about two degrees. The only other study we are aware of comparing the sidestep across maturation from the pre-pubertal age is the study by Sigward et al. (128). They got some similar results regarding the sex difference. In their study, females had higher peak abduction angle (but measured at different time frame in the stance phase) compared to men across all ages even though sex-maturation interaction was non-significant. In other words, it was apparent across mature groups and sexes in all age groups. However, when age groups were compared the adult group was the only one different from the others. They did not measure knee abduction excursion as was done in the present study. Therefore, that also makes the comparison a bit more complicated.

Effect of fatigue

The hypothesis that fatigue would increase knee abduction at IC and cause more excursion was supported in combination with higher maximal abduction angle during the 50% SP. This is in line with positions and movements that are thought to increase the risk of ACL injury and includes knee abduction and directly or indirectly multiplane knee valgus collapse (8, 19, 21, 23, 25, 149). This hypothesis is also based on the results of number of documented alterations in lower extremities and trunk after fatigue (38, 99-102). As we did not find any similar studies on the effect of fatigue on kinetics and kinematics in the knee during sidestep-cutting in the pre-pubertal population, we had to compare the results to studies on more mature groups (47, 48, 102, 112, 115, 117, 122).

In these studies there is divergence in the methodology to induce fatigue and how kinematic and especially the peak abduction angle is measured (that is, where in the stance phase). Similarly, there are equivocal results regarding the effects of fatigue on the motion in the knee. This complicates comparison between those earlier studies and the result of ours. It can though be concluded, based on these results, that the fatigue induces riskier pattern either by more erect position of the body in the sagittal plane or increased motion in the frontal and coronal planes. In the frontal plane this is like increased abduction in the knee and lateral flexion of the trunk towards the stance foot (47, 48, 102, 112, 115, 117, 122). Furthermore, there are two studies that rhyme with our results, the Borotikar et al. (102) and Tsai et al. (117) studies. These studies demonstrated increased peak abduction angles and had similar definition for it as was used in the current study. On the other hand, the sagittal data in this part of the project was not examined. These aforementioned results also strengthen the notion of task specificity of fatigue, i.e. related to fatigue protocol type, subjects, environment etc. (87, 89, 112).

The main reason for this movement strategy in the fatigued state by the children is uncertain, but several reasons could explain it. For one, this is a complicated motion pattern that the pre-pubertal individuals have not mastered and thus we would expect fatigue to induce riskier pattern in those individuals (128, 136, 137). This would be expected even though the present study does not include unanticipated condition that can further add to the riskier pattern (49).

Are the abduction angles measured in our study smaller or larger than in comparable studies? In our study we compared the peak angle during the 50% SP. In the study of Sigward et al. (128), among others, the peak was calculated by using weight acceptance defined as the period from initial contact to the first local minimum of the vertical GRF (first peak). The numbers in their study show around 5° abduction excursion. The values in the current study are from approximately 5-7° of abduction from pre- to post-fatigue. It would be reasonable to expect these values to be lower if the same formula was used as in the Sigward et al. study (128), as the maximum angle was usually at the end of the 50% SP in the current study. That is, the same timing as the second peak of the vertical GRF (see Figure 17). The first peak occurs much earlier in the stance phase (see

Figure **8**, Figure 14 and Figure 15). As in the study by Tsai et al. (117), the knee abduction range was from 4.4° to 7.7°, pre to post fatigue. This is interesting as in their study, subjects ran towards the force plate compared to one or two approach steps in the current study. It is tempting to conclude that these values should be higher if the subjects would have cut with greater force, both in the pre and post fatigued state. On the other hand, this is not certain but could make sense compared to the other studies as the pre-pubertal and pubertal subjects in the Sigward et al. (128) study moved significantly greater into abduction compared to the older young adults. This could support the hypothesis that pre-pubertal and pubertal individuals move into greater abduction during the movement compared to the more experienced adult athletes.

Effect of side

The hypothesis that main effect of side would influence the motion pattern in the knee was supported. The knee motion in frontal plane was riskier on the dominant right side as the IC and maximum angle in addition to the abduction excursion was significantly higher on that side. When looking closer at the maximum abduction angle there was a significant interaction of side and fatigue. The right side is obviously more fatigued in both sexes as reflected in Figure 11. Additionally when looking closer at the excursion there was a significant interaction between fatigue and sex meaning that fatigue affected one sex more than the other. Looking at Figure 12, it can be seen that that fatigue affects the women more than the males and more on the right side versus the left. This was reflected with the significant interaction of fatigue and side meaning that fatigue affected one side more than the other. Furthermore, the right side is more affected in both sexes though clearly more in the females.

As in the current study, the right dominant side of female field-hockey player was the one most affected by fatigue in the study by Weiss and Brown (73). Making the comparison little more complicated, is the fact that in their study the difference between sides was mainly based on moment, but in the current study higher abduction excursion was observed. Another factor making the interpretation of these result more complex and questionable of relevance is the fact that in the only study found on ACL tears and preferred kicking leg (dominant), soccer female players predominately tore their ACL on the non-dominant leg opposite to the male players (74). This raises the question of the relevance of the interactions of side and fatigue and fatigue and sex in relation to the maximum abduction angle and excursion, as this may be in contradiction to the predominant side of ACL tears in sample of female soccer players. Also, as mentioned before, the IC and the earlier position in the stance phase are possibly more relevant measurements. In the current study the sex difference regarding knee abduction excursion during the 50% SP in females is small and is difficult to assess in relation to the peak valgus moment during early stance and the peak ML-GRF, as the timing was not synchronized. However, the slightly higher values seen for boys for those variables in this study are seemingly not strongly affected by the abduction angle.

5.4 Knee frontal plane moment

Effect of sex

For the frontal plane knee moment, the hypothesis of no sex-difference was not supported as there was a significant main effect of sex demonstrated by higher first peak valgus moment by the boys during early stance. When looking at some of the factors that can explain this, like the GRF and the moment arm, the calculated medially horizontal force was marginally non-significantly higher in boys vs. girls. On the other hand weather it is first or second peak of the force within the 50%SP was not specified so its contribution can be questioned. As the moment arm was not calculated specifically, it is not possible to speculate about its contribution in this context. It is difficult to assert what the main reason for this sex-difference is, but as speculated before about the GRF, it must be combination of approach speed and technique. This is based on the fact that there were no injuries during the maneuver and the boys did not show riskier movement pattern for other variables, pre- or post-fatigue, that were calculated in this study. It is tempting to explain this higher value of abduction moment as a result of higher impact that resulted from more aggressive execution of the movement task.

On the other hand, the lower peak valgus moment seen in the girls during early stance is in contrast with the results of Sigward et al. (128) where the peak abduction moment was higher in pre-pubertal females compared to males even though non-significant and the effect size was 0.76. In addition, across sex the pre-pubertal athletes showed the most risky movement pattern for abduction moment and GRF. Higher GRF does not necessarily predict increased abduction moment, like demonstrated in the study of Kristianslund et al. (77) of self-selected game like sidestep cutting. The first peak abduction moment was much lower in our study or on average 0.40 and 0.26 Nm/kg for males and females, respectively, versus 1.6 Nm/kg in the Kristianslund et al. study (77). This is 4-6 times higher in their study and the abduction moment in their study was at least as high as in previous ones reported.

As noted in the study of Kristianslund et al. (77), the impulse will be lower with lower approach speed and cutting angle. In addition, the impulse correlated with maximum knee abduction moment. This was also reflected in the cutting technique and GRF. Higher GRF was associated with higher approach speed, smaller cutting angle and shorter cut time. Strongly connected to this is that the relations of the knee abduction moment arm of the GRF is stronger than its relations to its magnitude. This suggests the that alignment of the lower extremities are more important than the magnitude of the force of the abduction moment (77). Also, relevant to this and evident in the same study was the fact that increasing the knee valgus and cut width by 1 SD had more % increase on the knee abduction moment than approach speed. The variables that affected the moment arm the most were knee valgus and cut width. These are factors that positon the knee medially relative to the stance foot which increase the knee abduction moment arm and joint moment. Torso lateral flexion and rotation produce similar results on the moment arm of the knee abduction moment. This was for example is seen in the simulation study of Donnelly where the knee abduction moment was sensitiv se to the position (80).

In the current study there was no significant sex-difference for any variable in the frontal plane trunk motion and the difference seen for the knee abduction motion was small and only seen for total excursion in females. This supports the hypothesis that in this population of 10-12 years old athletic children, the higher abduction moment seen in boys was because they did the movement task with higher approach speed, quickness and impulse and therefore higher GRF. The larger abduction excursion seen in females might have been expected to increase the abduction moment, but this was not demonstrated by the results of the study, possibly due to the timing, as previously noted.

Effect of side

The lower peak varus moment on the right compared to left side may, in part, be due to the slight difference in maximal knee valgus angle, which was greater on the right side and may therefore serve to lower the varus moment. The peak varus moment generally occurred towards the mid-stance period, as did peak lateral flexion of the trunk, but correlation analysis did not indicate that maximal trunk angle influenced the varus moment.

5.5 Correlations

The regression analysis did not show any correlation between peak frontal plane moment during the 50% SP of stance phase and trunk lateral flexion as expected. There can be various reason for this. One is the low GRF and abduction moment. These variables were indeed lower than in comparable studies (72, 77). That suggests that the low speed of the maneuver did not induce enough lateral force that would translate into more lateral lean sway from the cutting direction and therefore induce changes in the moment into the direction of abduction towards mid-stance, where maximal trunk lean occurred.

The trend for a significant association between trunk angle at IC and the subsequent peak valgus moment during early stance indicates that trunk position during early stance may to some extent influence knee moments. However, the association was weak and other variables that affect knee joint loading in the frontal plane likely play a more important role.

5.6 Strengths and weaknesses of the study

Several strengths can be mentioned for this study. The data presented in this thesis is part of a larger cohort of data and a prospective study that is one of the first known to focus on several variables from the presumably pre-pubertal individuals (10-12 year old boys and girls) and comparing that data to comparable measurements on the same subjects when they will be 18-19 years old. These include, biomechanical variables, strength measures in hip and electromyography of the lower extremity muscles. The effect of sex, fatigue and side are examined on these variables using sidestep-cutting and DJ tests. In the older individuals, the effect of ACL preventive exercises are evaluated using the aforementioned variables and by relating them to ACL injured in the same sample of subjects. In cross-section specifically related to sidestep cutting and the pre-pubertal population, the effects of fatigue and side on biomechanical variables in trunk and lower extremity have not been studied to our knowledge. It is therefore a strength for this study to be able to look at data in a functional task like sidestep cutting and use it to shed a clearer light on the question if sex difference exists in pre-pubertal athletes for variables that are crucial for prediction of ACL injuries and if fatigue and side are important factors in that regard. At last, but not least, a large sample size is clearly also a strength for this study.

Several weaknesses can be mentioned for this study. The approach speed to the force plate was not standardized. One argument for this procedure is that differences between the subjects have the potential to affect GRFs and net joint moment calculations. Standardized approach speed will increase statistical power (77, 128). The approach speed often used in similar studies is from 4-5.5 m/s and the subjects are instructed to be within that range and often have several meters runway (7-8 m) to reach that speed (117). Sigward et al. (128) found that the pre-pubertal athletes had lower approach speed than the more mature groups. In our case it was decided after preliminary testing of the subjects that they would take one or two steps before they stepped on the force plate to ensure they hit it properly as they had difficulty doing so when approaching from longer distance at higher speed. Another method used by Kristanslund et al. (69, 77), is to use self-selected sport-specific sidestep cutting technique to get as functional realistic movement as possible. This was done with running approach and catching a ball before the cut. Their result were somewhat lower approach speed than seen in previous studies. It is difficult to get close to real life simulation of the sidestep cut in the lab. Our method demonstrated some sex-difference and effect of the fatigue but it can be argued that faster approach speeds would have given higher values and variability due to higher forces that would be more difficult to control. Furthermore, it would have helped with the interpretation of the results if the approach speed was measured regarding variables like the GRF where there was a sex difference.

Another potential weakness is the lack of using unanticipated sidestep cutting like has been demonstrated to induce riskier movement pattern with and without fatigue (49, 102, 148). Unplanned sidestepping is thought to more closely emulate game scenarios by limiting decision time, increasing knee loading and challenging the integrity of soft-tissue structures in the knee. On the other hand this has been questioned, like by Kristanslund et al. (69, 77) where they use their self-selected methods to get similar game like effects.

Functional relevance of the fatigue protocol can always be questioned. One perspective is how its effects transfers to the functional task like side-step cutting. Their design are very diverse in different studies and can include non-functional or functional protocols, and short or long-term functional protocols. In addition, the results show great degree of variability and task specificity and difficult to tell if they produces similar fatigue pattern, occurring on the field during match. On the other hand five minute short term functional protocols have significantly altered biomechanical variables (112). Even though the protocol used in the current study has not been used before in any study. Nevertheless, it produced enough rating on a perceived exertion scale to produce fatigue effects. Other measures like heart rate could have strengthened the rating of fatigue considering its relations to anaerobic threshold. Another potential weakness is the selection of where in the stance phase the angles in the knee and the ML-GRF are measured as mentioned above. Measuring these variables closer to the time frame of potential ACL rupture at the first peak of the GRF could be more relevant instead of within the whole timeframe of the 50% SP.

At last, but not least, there was no standardized measurement of the pubertal stage. This is sometimes done to ensure that the subjects belong to the right maturational group and the fact that the stages of pubertal development generally coincide with changes in physical characteristics. Different self-report scales can be used for this matter (128). In our study the demographic data shows no difference between sexes. There were very few outliers in the two groups and the average age about 10.5 years. The age when the sex disparity in ACL injury appears, is around the time of the growth spurt, 12-14 years in girls and 14-16 in boys (2, 31). Both of these factors indicate that our group is within this limit and could present the pre-pubertal population.

6 Conclusion

One of the main findings of this study were significant differences between the sexes for kinematic and kinetic measures suggesting that a sex difference in movement patterns already exists before puberty. This was demonstrated by significantly higher knee abduction moment in boys compared to girls and higher knee abduction excursion in girls compared to boys. These result do not clearly indicate which sex demonstrated riskier movement pattern regarding ACL injury risk, only that there are differences between the sexes. Other important findings of this study indicate that five minute fatigue protocol affects movement pattern measured by kinematic and kinetic changes and thereby the knee joint loading during sidestep cutting maneuver of both boys and girls. This was evident by more ipsilateral trunk flexion toward the stance foot, more abduction of the knee and higher maximal ML-GRF. These movement patterns correlate with increased knee joint loading and movement pattern thought to possibly stress the ACL ligament. Interaction of fatigue and sex, and side and fatigue, on the knee kinematics and kinetics resulted in the greatest valgus angles and excursion in the right knee of the girls indicating risky motion pattern.

These kinematic and kinetic differences observed for sex, fatigue and side are factors that can be of possible risk for ACL injury during the maturation years. It can also be argued that the results of this study further strengthen the data that already indicate that it is best to start preventive exercises and measures for optimal ACL injury risk reduction during pre- or early adolescence, i.e. before the period of altered mechanism that increases injury risk and before the peak in injury incidence. These preventive measures might have to be specialized for boys and girls separately at some stage and be part of athletic training. Fatigue and side would also have to be considered in this context. The take home message is that biomechanical differences between the sexes are evident earlier than previously thought. If the right measures are taken, the rate of ACL injuries could be reduced particularly among the females. This strengthens the motive to study better movement patterns in pre-pubertal athletes in relation to ACL injury risks and sidestep cutting can be a valuable tool in that context.

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Appendix I

Kynbundin áhætta krossbandaslits: aldurstengdar breytingar hjá ungmennum sem stunda handbolta og fótbolta.

Samstarfsyfirlýsing forráðamanna íþróttafélaga

Samstarf þetta felst í að leyfa kynningu á ofangreindri rannsókn innan þess íþróttafélags sem undirritaður er í forsvari fyrir.

Með mínu samþykki munu þjálfarar, íþróttamenn sem uppfylla aldursþátttökuskilyrði og forráðamenn íþróttamanna (eftir því sem við á, aldurs vegna) fá sent kynningarbréf þar sem skýrt er frá tilgangi rannsóknar og framkvæmd.

Ég staðfesti hér með undirskrift minni að ég hef lesið upplýsingarnar um rannsóknina sem mér voru afhentar, lesið kynningarbréf það sem sent verður út, og hef fengið tækifæri til að spyrja spurninga um rannsóknina og fengið fullnægjandi svör og útskýringar á atriðum sem mér voru óljós.

Samþykki þetta er veitt með fyrirvara um samþykkt Vísindasiðanefndar og Persónuverndar.

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Staður og dagsetning

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Undirskrift og kennitala / Nafn íþróttafélags

Undirritaður, starfsmaður rannsóknarinnar, staðfestir hér með að hafa veitt upplýsingar um eðli og tilgang rannsóknarinnar, í samræmi við lög og reglur um vísindarannsóknir.

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Appendix II

Letter of introduction

Rannsókn á vegum Rannsóknarstofu í hreyfivísindum við Heilbrigðisvísindasvið Háskóla Íslands

Kynbundin áhætta krossbandaslits: aldurstengdar breytingar hjá ungmennum sem stunda handbolta og fótbolta.

Tilgangur: Krossbandaslit eru ein af alvarlegustu meiðslum sem íþróttamaður getur lent í og reikna má með að endurhæfing taki allt að 6-12 mánuði áður en leikmaður er fær um að snúa aftur til keppni. Þeir sem slitið hafa krossband fá fyrr en ella slitbreytingar í hnéliðinn, sem hefur áhrif á líkamlega virkni og lífsgæði til lengri tíma litið. Algengast er að meiðslin eigi sér stað við snögga stefnubreytingu eða lendingu úr stökki, án nokkurrar snertingar við mótherja. Stjórn hreyfinga um liði neðri útlima skiptir þarna höfuðmáli.

Markmið rannsóknarinnar er að kanna þær breytingar sem verða á hreyfistjórn við kynþroska hjá heilbrigðu íþróttafólki af báðum kynjum og áhrif sérhæfðra æfinga þar á. Hreyfimynstur, sem og tímasetning og magn vöðvavinnu, verða mæld við stökk og við að breyta um hlaupastefnu. Styrkur helstu vöðvahópa ganglima verður einnig metinn til að kanna tengsl milli hreyfinga, vöðvavirkni og –styrks. Kvenkyns 11-12 ára þátttakendum verður síðan skipt í tvo hópa þar sem annar hópurinn gerir sérhæfðar æfingar yfir 3-4 ára tímabil áður en mælingar eru endurteknar. Niðurstöður rannsóknarinnar munu auka þekkingu okkar og skilning á þeim áhættuþáttum krossbandaslita sem hægt er að hafa áhrif á og draga þannig úr tíðni meiðslanna.

Ábyrgðarmaður rannsóknarinnar er Dr. Kristín Briem, dósent við Námsbraut í sjúkraþjálfun, Háskóla Íslands. Vinnusími: 525-4096, tölvupóstur: kbriem@hi.is

Aðrir rannsakendur er einn lektor í íþrótta- og heilsufræðum og tveir sjúkraþjálfarar, sem eru í rannsóknartengdu meistaranámi í hreyfivísindum við Læknadeild H.Í:

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- Hjálmar Jens Sigurðsson.

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Framkvæmd: Sóst er eftir þátttöku íþróttafólks af höfuðborgarsvæðinu. Mælingar fara fram á Rannsóknarstofu í hreyfivísindum (Námsbraut í sjúkraþjálfun) og tekur um 75 mínútur. Fyrst eru límdir nemar á helstu vöðvahópa fótleggja, en þeir ‚hlusta' eftir því hvernig og hvenær vöðvarnir vinna. Síðan er létt upphitun á hjóli, og styrkur helstu fótleggjavöðva mældur og framkvæmd almenn skoðun á líkamsbyggingu. Endurskinskúlur verða festar með teygju eða límbandi á ganglimi og bol þátttakenda, sem klæðast stuttbuxum og bol. Myndavélar, sem gefa frá sér ljós, nema endurvarpið frá kúlunum og fylgja þannig hreyfingum kúlnanna eftir, þegar: a) framkvæmt er stökk niður af 20-30 cm háum kassa; og b)gabbhreyfing er gerð (eins og til að komast framhjá andstæðingi). Eftir þessar mælingar er gerð sérstök æfing til að auka almenna vöðvaþreytu, en að því loknu eru mælingar endurteknar á stökki og gabbhreyfingu, til að meta áhrif þreytu á hreyfimynstur og vöðvavirkni.

Ávinningur/áhætta af þátttöku: Þátttakandi fær upplýsingar um eigin styrk og líkamsbyggingu, og óbeinan ávinning vegna aukinnar þekkingar á áhrifum sértækrar þjálfunar eftir að niðurstöður rannsóknarinnar koma í ljós. Áhætta af þátttöku er lítil; mælingar fara fram í öruggu umhverfi án truflana. Þátttakendur geta því einbeitt sér að þeim æfingum sem framkvæmdar eru, sem er mikilvægt eftir að þeir þreytast. Æfingarnar eru staðlaðar og felast í hreyfingum sem þátttakendur þekkja vel af æfingum og úr keppni í sinni íþrótt. Hugsanlegt er að einstaklingar með viðkvæma húð finni fyrir tímabundinni ertingu undan elektróðum eða límbandi sem notað er til að festa endurskinskúlur á húð, en slíkt er þó óvanalegt. Þátttakendur eru tryggðir gegn óhöppum, enda þótt áhættan sé afar lítil.

Trúnaður og gagnaöryggi: Rannsakandi heitir fullum trúnaði við þátttakendur. Gagnaúrvinnsla fer fram í tölvu, gögn sem auðkennd eru einungis með númeri, eru geymd þar undir lykilorði sem rannsakendur hafa einir aðgang að. Skrifleg gögn, auðkennd með númeri, verða geymd í læstri hirslu. Þátttakendur geta hætt þátttöku í rannsókninni á hvaða stigi hennar sem er án skýringa eða eftirmála. Vakni einhverjar spurningar má leita til starfsfólks rannsóknarinnar eftir nánari upplýsingum, eða til Vísindasiðanefndar (sjá neðanmáls). Ekki er greitt fyrir þátttöku, en forráðamönnum íþróttafélaga, og þátttakendum, verður boðið að þiggja fræðsluerindi um niðurstöður rannsóknarinnar, hvort sem þeir lenda í rannsóknar- eða viðmiðunarhóp.

Niðurstöður rannsóknarinnar verða birtar í meistara og doktorsritgerðum, en einnig mun stefnt að því að birta niðurstöður á ráðstefnum og í ritrýndum vísindaritum. Persónugreinanlegar upplýsingar munu hvergi koma fram opinberlega.

Með fyrirfram þökk og von um jákvæðar undirtektir.

Appendix III

Háskóli Íslands Læknadeild

Rannsóknarstofa í hreyfivísindum Námsbraut í sjúkraþjálfun

Rannsókn á vegum Námsbraut í sjúkraþjálfun við Heilbrigðisvísindasvið Háskóla Íslands; ***Kynbundin áhætta krossbandaslits: aldurstengdar breytingar hjá ungmennum sem stunda handbolta og fótbolta.***

SAMÞYKKISYFIRLÝSING FYRIR UNGA ÞÁTTTAKENDUR

Rannsóknir hafa sýnt að þótt strákar og stelpur hreyfi sig á svipaðan hátt þegar þau gera gabbhreyfingar eða stökk, þá gera karlar og konur það ekki. Ekki er vel þekkt hvað veldur þessu, eða hvort það hefur áhrif á t.d. meiðsli. Markmið rannsóknarinnar er að komast að því hvaða hlutir breytast hjá stelpum og strákum við kynþroska og hvort þjálfun skiptir máli. Hreyfimynstur og vöðvavinna verða mæld við stökk og við að breyta um hlaupastefnu. Niðurstöður rannsóknarinnar munu auka þekkingu okkar á áhættuþáttum meiðsla og áhrifum æfinga, svo við getum kannski dregið úr meiðslahættu.

Þátttaka í rannsókninni felur í sér að mæta með strigaskó, stuttbuxur og bol á stofu í Háskóla Íslands, þar sem mælitæki og nemar verða sett á líkamann. Þetta gerum við til að hlusta á hvernig vöðvarnir vinna og mæla hvernig liðamótin hreyfast. Einnig verður hæð og þyngd mæld. Mestur tíminn fer í að stilla upp og setja mælitækin á sinn stað, en svo fara mælingar fram. Þetta tekur alls um 2 klst. Einhverjir þátttakendur verða beðnir um að koma aftur í mælingar eftir nokkur ár.

Ég staðfesti hér með undirskrift minni að ég hef lesið upplýsingarnar um rannsóknina sem mér voru afhentar, og hef fengið tækifæri til að spyrja spurninga um rannsóknina og fengið útskýringar á öllu sem ég spurði um. Ég vil taka þátt í rannsókninni, en veit að ég má hætta við hvenær sem ég vil þó ég hafi skrifað undir þetta blað. Ef ég vil hætta við að taka þátt þarf ég ekki að útskýra hvers vegna og það breytir engu fyrir mína íþróttaiðkun eða læknisþjónustu í framtíðinni.

Ég veit að útkomunum úr mælingunum verður eytt að rannsókn lokinni og að þátttakendur eru tryggðir fyrir óhöppum sem hugsanlegt er að verði á meðan æfingar eru gerðar í rannsókninni.

Dagsetning

Undirskrift og nafn þátttakanda (barns)

Undirritaður, starfsmaður rannsóknarinnar, staðfestir hér með að hafa veitt upplýsingar um eðli og tilgang rannsóknarinnar, í samræmi við lög og reglur um vísindarannsóknir.

Nafn rannsakanda

Appendix IV

Marker setup

Anatomical markers	Name	Number
Location	(R=right; L=left)	
Cervical vertebra 7	C7	1
Thoracic vertebra 10	T10	1
Acromion	RAC/LAC	2
Manubrium of Sternum	Sternum	1
Sacrum	Sacrum	1
Posterior Superior Iliac Spine	RPSIS/LPSIS	2
Anterior Superior Iliac Spine	PSIS/ASIS	2
Crista Iliaca	RCI/LCI	2
Greater Trochanter	RGT/LGT	2
Lateral Knee	RLK/LLK	2
Medial Knee	RMK/LMK	2
Additional tracking markers		
Location	(R=right; L=left)	
Thigh	RTH1-4/ LTH1-4	8
Shank	RSH1-4/LSH1-4	8
Ankle	RLMAL/LLMAL	2
	RMMAL/LMMAL	2
Foot	RHEELH/LHEELH	2
	RHEELL/LHEELL	2
	RTOE1/RTOE5	2
	LTOE1/LTOE5	2