WATCH YOUR STEP! IS FOOT LANDING TECHNIQUE DURING CUTTING MANOEUVRES ASSOCIATED WITH ACUTE LOWER EXTREMITY INJURIES?

A 12–Month Prospective Cohort Study of Young Team Sport Athletes

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TIIVISTELMÄ

Vornanen, T. 2019. Varo miten astut! Onko nopeiden suunnanmuutosten yhteydessä esiintyvällä jalkaterän laskeutumistekniikalla yhteys akuutteihin alaraajavammoihin? 12kk prospektiivinen nuorten palloilijoiden kohorttitutkimus. Liikuntatieteellinen tiedekunta, Jyväskylän yliopisto, Liikuntalääketieteen pro gradu -tutkielma, 89 s.

Useita pallopelejä luonnehtivat erilaiset nopeat suunnanmuutokset sekä äkilliset kiihdytykset, mitkä altistavat etenkin nuoria urheilijoita akuuteille alaraajavammoille. Aiempien tutkimusten valossa on esitetty, että jalkaterän laskeutumistekniikka saattaisi olla yhteydessä vammariskiin sekä erityyppisiin juoksuvammoihin. Hyvin vähän tiedetään kuitenkin jalkaterän laskeutumistekniikan yhteyksistä alaraajojen kinematiikkaan erityisesti nopeiden suunnanmuutosten aikana. Tämän tutkimuksen tarkoituksena oli selvittää, onko nopeiden suunnanmuutosten yhteydessä esiintyvällä jalkaterän laskeutumistekniikalla yhteys nuorten palloilijoiden akuutteihin, ilman suoraa kontaktia, tapahtuneisiin nilkan- ja polven nivelsidevammoihin.

Tutkimus on osa laajempaa, Tampereen urheilulääkäriaseman ja UKK-instituutin yhdessä toteuttamaa, prospektiivista PROFITS-tutkimusta (Polvi- ja nilkkavammoja ennustavat tekijät sekä vammojen ehkäisy nuorilla urheilijoilla), mikä on toteutettu Tampereella vuosina 2011–2015. Yhteensä 183 koripalloilijaa ja 172 salibandyn pelaajaa (12-21v.) osallistuivat 3D-liikelaboratoriossa toteutettuihin kahteen erilaiseen suunnanmuutostestiin (90° & 180° testit). Seuraavat kinemaattiset muuttujat analysoitiin pelaajien suorituksista alustakontaktihetkellä: (1) nilkan dorsi-/plantaarifleksio, (2) nilkan inversio/eversio, (3) nilkan sisä-/ulkorotaatio, sekä (4) jalkaterän askelluskulma alustaan nähden. Kaikki yhden vuoden seurantajakson aikana ilmaantuneet polven ja nilkan nivelsidevammat sekä pelaajien ottelu- ja harjoitustunnit kirjattiin. Coxin regressioanalyysin avulla laskettiin riskitiheyssuhteet sekä 95%:n luottamusvälit.

Seurannan aikana rekisteröitiin yhteensä 38 nilkan nivelsidevammaa (0,24 vammaa/1000 peli- ja harjoitustuntia) sekä 16 polvivammaa (0,10 vammaa/1000 peli- ja harjoitustuntia). Tulokset osoittavat, että transversaalitasossa tapahtuva jalkaterän sisäkierto oli tutkituista muuttujista ainoana tilastollisesti merkitsevästi yhteydessä seurantajakson aikana ilmaantuneeseen nilkkavammaan. Tämä yhteys havaittiin molemmissa suunnanmuutostesteissä. 90° testissä jokainen 5° lisäys jalkaterän sisäkiertoon kasvatti uuden nilkkavamman riskin 1,16 kertaiseksi (p=0,045; 95% CI, 1,00-1,35), kun taas 180° testissä jokainen 5° lisäys oli yhteydessä 1,14 kertaiseen riskiin saada uusi nilkkavamma (p=0,01; 95% CI, 1,03-1,26). Tilastollisesti merkitsevää yhteyttä vammoihin ei havaittu muiden tutkittujen muuttujien osalta. ROC-käyrän avulla tehty analyysi viittasi jalkaterän sisäkierron ja vammojen ilmaantuvuuden väliseen erittäin heikkoon ennustettavuuteen (yhdistetty sensitiivisyys ja spesifisyys).

Tämän tutkimuksen tulokset antavat viitteitä jalkaterän sisäkierron mahdollisesta yhteydestä nilkkavammariskiin, joskin mitään erityisen selvää laskeutumistekniikkaa ei voida tulosten perusteella yhdistää alaraajavammojen ilmaantuvuuteen. Kantapää edellä tapahtuva askellus, minkä on esitetty olevan vammoille alttiimpi tekniikka verrattuna päkiäaskellukseen, ei tässä tutkimuksessa ollut millään tavalla yhteydessä alaraajavammojen ilmaantuvuuteen. Lisäksi jalkaterän sisäkierron ei havaittu olevan yhteydessä polvivammojen ilmaantuvuuteen, toisin kuin aiemmissa tutkimuksissa on ehdotettu. Tulosten perusteella voidaan todeta, että pelaajien tulisi suunnanmuutosten yhteydessä, vammoja ehkäistäkseen, pyrkiä välttämään liiallista jalkaterän sisäkiertoa alustakontaktihetkellä. Jatkossa toteutettavien tutkimusten tavoitteena tulisi olla vahvistaa tässä tutkimuksessa esitetyt tulokset suurempien otoskokojen avulla sekä hyödyntäen erilaisia suunnanmuutostestejä eri lajien urheilijoilla.

Asiasanat: ACL; nilkan nyrjähdys; suunnanmuutos; riskitekijät; urheilu.

ABSTRACT

Vornanen, T. 2019. Watch Your Step! Is Foot Landing Technique During Cutting Manoeuvres Associated with Acute Lower Extremity Injuries? A 12-month prospective cohort study of young team sport athletes. Faculty of Sports and Health Sciences, University of Jyväskylä, Master's Thesis, 89 pp.

Many pivoting sports that requires rapid turns and accelerations to various directions may entail a high risk for acute lower extremity injuries, particularly, for adolescents. The previous findings have indicated that the foot strike technique may be related with injurious lower extremity biomechanics, as well as to a specific lower limb running injuries. Yet, there are not too many research papers investigating the foot landing pattern associated with lower extremity kinematics during athletic tasks. Therefore, the purpose of this study was to investigate the association of the foot landing pattern during cutting maneuvers to the incidence of acute noncontact knee and ankle ligament injuries among young team sport athletes.

The current study was carried out at the Tampere Research Center of Sports Medicine and the UKK Institute for Health Promotion Research, Tampere, Finland. This study is part of the large prospective PROFITS-study (Predictors of Lower Extremity Injuries in Team Sports) conducted in Finland between 2011 and 2015. A total of 183 basketball and 172 floorball players (age range, 12-21 years) participated in two cutting technique procedures (90° and 180° tests) conducted in the 3D motion analysis laboratory. The following kinematic variables were analyzed: (1) ankle dorsi-/plantarflexion at initial contact (IC), (2) ankle inversion/eversion at IC, (3) ankle internal/external rotation at IC, and (4) foot strike angle at IC. All knee and ankle ligament injuries, as well as match and training exposure, were then recorded for the following 1-year. Cox Regression models were used to calculate hazard ratios (HRs) and 95% CIs.

During the follow-up a total of 38 noncontact ankle ligament injuries (0.24 injuries/1000 player-hours) and 16 noncontact knee injuries (0.10 injuries/1000 player-hours) were registered. Of the variables investigated, only the transverse plane foot internal rotation, in both cut tasks, were significantly associated with a new ankle injury. During the 90° cut, each 5° increase in foot internal rotation was associated with a 1.16 times higher risk for ankle injury (p=0.045, 95% CI, 1.00-1.35), whereas during the 180° cut each 5° increase in foot internal rotation was associated with a 1.14 times higher risk for ankle injury (p=0.01, 95% CI, 1.03-1.26). No significant association was observed in any other kinematic variable investigated. ROC curve analysis for foot internal rotation at IC showed an area under the curve of 0.6, indicating a poor combined sensitivity and specificity of the test.

The findings of this study demonstrated that, while there was some relation of foot internal rotation at IC on ankle injuries, no clear landing pattern could be described as strongly associated with lower extremity injuries. The heel strike pattern, particularly, which have been suggested to be harmful landing technique compared to forefoot striking during cutting tasks, wasn't found to be related to lower limb injuries. Furthermore, internal rotation of the foot wasn't associated to knee injuries as has been previously hypothesized. Based on these results, avoiding excessive internal rotation of the foot when cutting may reduce the risk for ankle injuries. The future studies should confirm these findings with the utilization of various cutting procedures, larger sample sizes and athletes representing different sports.

Key words: ACL; ankle sprain; cutting; risk factors; team sports.

ABBREVIATIONS

AE	athletic exposure: One athlete participating in one practice or competition where he or she is exposed to the possibility of athletic injury.
ACL	anterior cruciate ligament
ATFL	anterior talofibular ligament
CFL	calcaneofibular ligament
CI	confidence interval
GRF	ground reaction force
HR	hazard ratio
IC	initial contact
LCL	lateral collateral ligament
MCL	medial collateral ligament
PCL	posterior cruciate ligament
PTFL	posterior talofibular ligament
ROC	receiver operating characteristic
ROM	range of motion
RR	risk ratio
PROFITS	Predictors of Lower Extremity Injuries in Team Sports (study)
SD	standard deviation
3D	three-dimensional

CONTENTS

1 INTRODUCTION

Due to its many physical and physiological health benefits, people all around the world are encouraged to participate in sporting activities (Fong et al., 2007). It's worth noting, that significant number of children aged 5–18 years are competing in organized sports (Adirim & Cheng 2003), where the injury rates seems to be higher than in other leisure-time physical activities (Räisänen et al., 2016). Generally, competing in youth team sports is considered to be safe, however, the risk of injury is always present in certain sports, for both the elite and recreational athletes (Bahr & Krosshaug 2005). Particularly, many pivoting sports that requires rapid turns and accelerations to various directions (e.g., basketball, soccer, handball, floorball), may entail a high risk for acute (Hootman et al., 2007) and overuse (Leppänen et al., 2017) lower extremity injuries for adolescents.

It's widely recognized that many of the noncontact sports injuries have a mechanical cause related to biomechanical factors, such as the forces and temporal characteristics of the movement (Murphy et al., 2003; Read et al., 2016). However, there is still a lack of knowledge of which biomechanical components are essential for reducing lower limb injuries (Bahr & Krosshaug 2005). Several studies have placed a closer look on knee and hip parameters during landing tasks to identify abnormal movement patterns, yet there are not too many research papers investigating the foot landing pattern associated with lower extremity kinematics during cutting manoeuvres (Sugimoto et al., 2015; Weiss & Whatman 2015). The previous findings, however, have indicated that the foot strike technique (e.g., foot strike angle or internal rotation of the foot at initial contact) may be related with injurious lower extremity biomechanics (Donnelly et al., 2017), as well as to a specific lower limb running injuries (Altman & Davis 2016). These findings, therefore, emphasizes the need for in-depth knowledge of the foot and ankle biomechanics related to sport injuries.

The purpose of this study is to investigate the association of the foot landing pattern during cutting manoeuvres to the incidence of acute noncontact knee and ankle ligament injuries among young team sport athletes. To my knowledge, there is no previous prospective studies to done this. The aim of this study is to provide new evidence for the professionals working with athletes to help to develop even more successful injury reduction/prevention programs.

I wish to express my gratitude for my supervisors Mari Leppänen, PhD, and Ina Tarkka, PhD, for their guidance and support through this process. I would also like to thank the UKK Institute and Tampere Research Center of Sports Medicine for providing me the facilities, as well as the opportunity to learn and to be part of this interesting study. Furthermore, I would like to thank the personnel of the Institute of their help for processing the study data. Lastly, I would like to thank Juha-Pekka Kulmala, PhD, for providing me with some helpful tips at the beginning of this process and consulting whenever needed.

2 BIOMECHANICS OF SPORT & EXERCISE

2.1 Key Anatomical & Mechanical Concepts Used in Sport Science

In biomechanics, the movement of the living things are studied using the science of mechanics (Knudson 2003, 3; McGinnis 2013, 3). Sport biomechanics research is mainly based on rigid-body models, which could be divided into static and dynamics. Dynamics is interested to study how objects are being accelerated by the action of forces and, furthermore, could be divide into two branches: kinematics (motion description) and kinetics (causes of motion) (Knudson 2003, 24).

Internal & External Forces. When studying biomechanics, it's important to understand the forces acting on body, since they enable us to move in various directions with multiple speeds. Forces can be classified as *internal* or *external*. Internal forces are forces that "act within the object or system whose motion is being investigated", while external forces "act on an object as result of its interaction with the environment surrounding it". (McGillis 2013, 21.) Both internal and external forces are essential when analyzing human movement, since both forces can generate rotational effects acting on our body. A rotating effect produced by a force is called a *moment of force* (also torque or sometimes shortened as moment), and it's something that causes an object to have angular acceleration. Muscles, for instance, create moments about joints and create angular motion of the limbs. These internal moments, generated by muscles in relation to the joint rotation axis, are important, not just by creating general movements of the limbs, but also, for counterbalancing the external moments which, especially in high activity sports, tend to increase the rotational loads for passive structures, such as ligaments and joints. (Knudson 2003, 167–172; McGinnis 2013, 134–139.)

Planes of Motion & Axis of Rotation. Motion of bones are conventionally described relative to the three cardinal (principal) planes of the body: sagittal, frontal and transverse (Figure 1). These planes could be visualized as dimension of motions to a specific direction. *The sagittal plane* divides the body into right and left sections. Common terms used to describe motions in this plane are flexion and extension, such as dorsi- and plantarflexion of the foot. *The frontal* *plane* bisects the body into front and back sections. Main motions occurring in this plane are abduction and adduction, as well as inversion and eversion of the foot. *The transverse plane* divides the body into upper and lower sections. Common terms used to illustrate motions in this plane are internal and external rotations. Furthermore, bones tend to rotate around a joint in a plane that is perpendicular to an *axis of rotation*. Anatomical axis could be visualized as a straight imaginary line about which a body part rotates (Figure 1). The line of *anteriorposterior axis* (also sagittal axis) passes horizontally through a joint from front to back and is perpendicular to the frontal plane. *Mediolateral axis* (also transverse axis, horizontal axis, frontal axis) runs horizontally left to right and is perpendicular to the sagittal plane. Longitudinal axis (vertical axis) passes the joint superior to inferior and is perpendicular to the transverse plane. (Knudson 2003, 42; McGinnis 2013, 200; Neumann 2010, 5.)

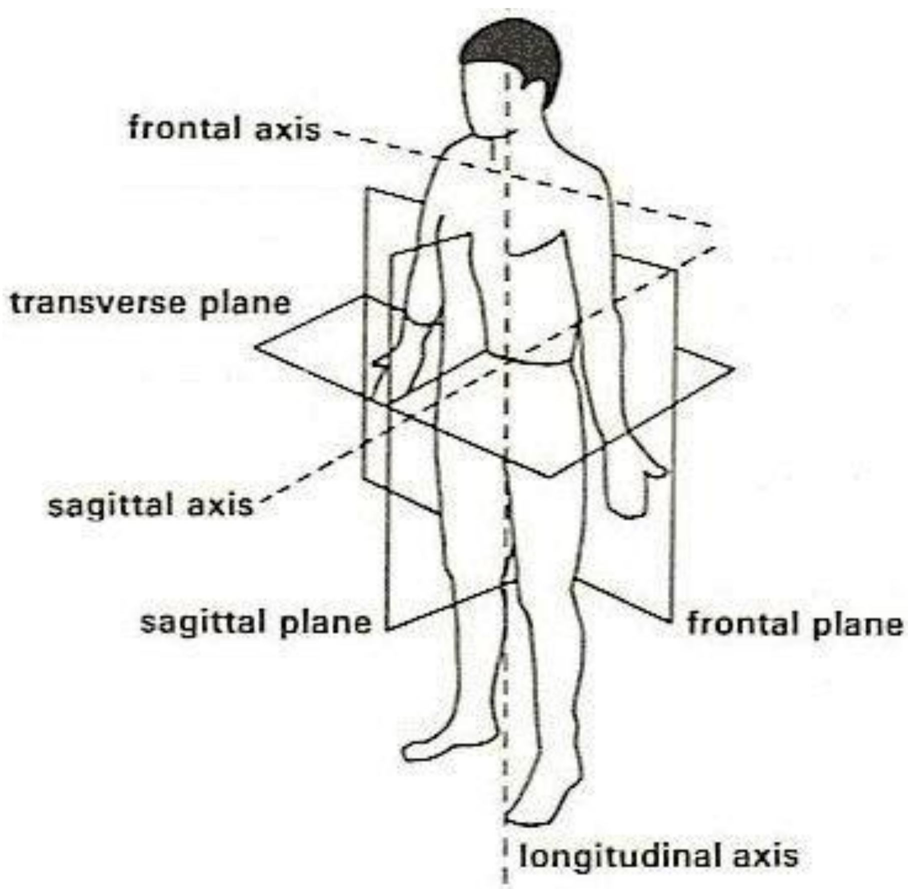

FIGURE 1. Sato, T. D. O., et al. 2010. Principal anatomical planes of motion, and axes of rotation. In Goniometer crosstalk compensation for knee joint applications. Sensors, 10 (11), 9994-10005.

2.2 ‘Cutting Manoeuvres’ in Team Sports

Sheppard and Young (2006) have described the term ‘agility’ as “a rapid whole-body movement with change of velocity or direction in response to a stimulus”. They also state that the term ‘cutting’ has been used in the sport literature and can be described as “a change of direction during a sprint movement”. More precisely, according to Sheppard and Young, ‘cutting’ comprises only the specific segment of directional change, where the athlete lands the foot on the ground and orientate oneself to a new direction. Furthermore, Brughelli and colleagues (2008) emphasizes that ‘change of direction’ is a component of agility, which has been recognised as an essential skill in various sports of modern era (Brughelli et al., 2008); and furthermore, demonstrated to indicate the level of talent of soccer players (Reilly et al., 2000).

In soccer, for example, the player performs an average of 727 turns and swerves during match-play, and these cutting motions are frequently observed in situations where the player attempts to possess the ball or to deceive an opponent. Furthermore, these directional changes are quite frequently performed between angles 0° to 180°. (Bloomfield et al., 2007.) Similarly, basketball requires the players to jump and land frequently and, additionally, to perform directional reorientations every 2 to 3 seconds (Roos et al., 2017). Floorball is a fast-paced indoor ball game characterized by rapid accelerations, sudden stops and quick cutting manoeuvres (Tranaeus et al., 2016) – yet, previous studies haven’t quantified the precise amount of directional changes occurring during the game. Floorball, according to the rules, has been defined as a noncontact sport, however, due to the fast-pace of the game, direct collisions to another player and contacts with sticks and ball are commonly observed (Pasanen et al., 2008).

To further clarify some of the terms used in the following chapters, according to Brown and colleagues (2014), the term ‘cutting’ or ‘cutting manoeuvre’ is a synonymous to ‘sidestepping’ or ‘side-step’, which has been defined as acceleration toward the direction opposite of the planted leg (Potter et al., 2014) – and usually performed as a 45° or 90° rapid cut (Cortes et al., 2011; Jones et al., 2014). Furthermore, ‘pivot task’ or ‘pivoting manoeuvre’, as well as ‘crossover cut’ are different from ‘sidestep cutting’. Pivoting is used to describe a manoeuvre that involves a 180° rapid turn after a straight run followed by a quick sprint back to the starting position (Cortes et al., 2011; Jones et al., 2014), whereas crossover cut is defined as crossing one leg over the planted leg and accelerating in the same direction of the push off leg (Potter et al., 2014). Brown and colleagues (2014) also state that 'planned' task could be used as a synonymous with 'preplanned' and 'anticipated', while an 'unplanned' task is synonymous with 'reactive' and 'unanticipated'. All these terms are often used in the sport literature and, furthermore, it has also been shown that the differences between these tasks place the athlete at varying levels of risk for sustaining a lower extremity injury (Besier et al., 2001; Potter et al., 2014). In the present thesis, the term 'cutting manoeuvre' is used to describe any type of *change of direction task* illustrated above.

2.3 Whole Body Biomechanics During Directional Changes

Several biomechanical studies have been carried out to describe, in a detailed manner, how cutting tasks, or certain components of the movement, could be performed as quickly as possible (Fox 2018; Dos Santos et al., 2018; Jones et al., 2016a). Additionally, cutting manoeuvres have gathered much interest among researchers in the past few decades due to their strong association with lower extremity injuries (Jones et al., 2014).

Changing direction in sports could be visualized as *a one coherent and smooth ongoing motion that involves the braking, translation and reorientation phases*, and thus the whole body needs to adjust for these quick movement patterns (Havens & Sigward 2015a). This is mainly accomplished by altering and adjusting the body's position and velocity. *Center of mass* (COM) and *center of pressure* (COP), as well as *ground reaction forces* (GRF) and *ground reaction impulses* (GRI) are some key biomechanical variables of which relations to each other effects on how loads are absorbed by different segments of the body. (Havens & Sigward 2015b.)

For instance, when decelerating COM moves posterior relative to COP and this generates posteriorly directed (braking) GRF. Consequently, lower extremity extensor muscles, such as plantar flexors and gluteus maximus, increase their activity during this breaking phase to decelerate the body. (Havens & Sigward 2015b.) Furthermore, during redirection phase the body attempts to align and orientate to a new direction. Translation of the COM into a new travel path involves the athlete to place the foot laterally and lean the trunk away from the body.

COM and COP, therefore, separates further from each other in medial–lateral course, while a medially directed GRF is generated (Figure 2). Rotational moments, additionally, are present during change of direction as the whole body rotates along the vertical axis, while in transverse plane the body segments from head to toes re-orientates in sequence. (Havens 2013, 9–11; Havens & Sigward 2015b.)

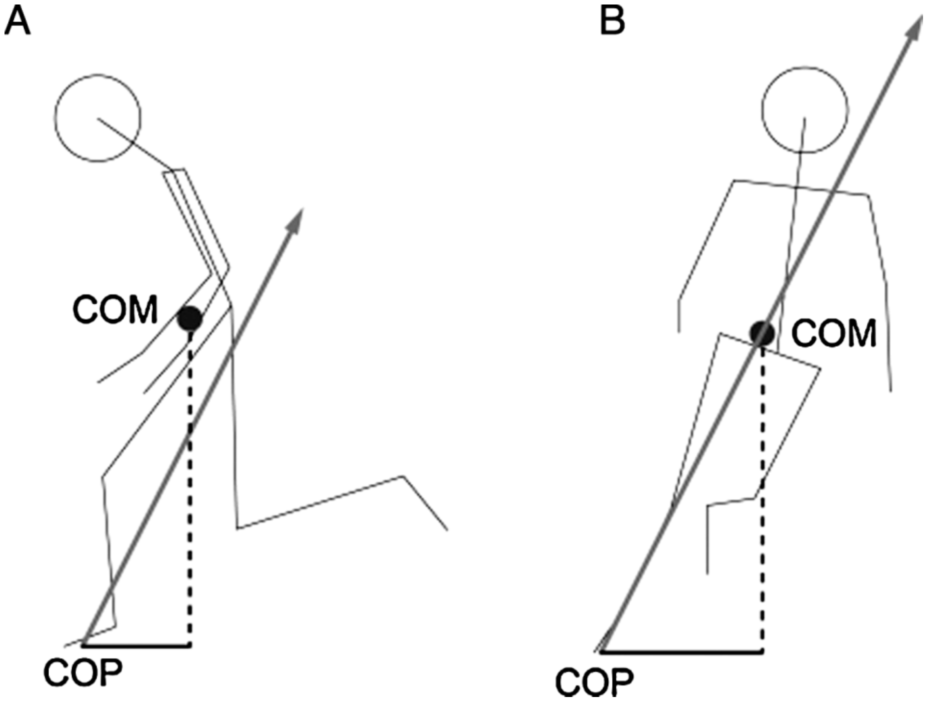

FIGURE 2. Havens, K. L., & Sigward, S. M. 2015. Figure illustration of how during cutting the center of mass (COM) and center of pressure (COP) tend to separate: both in anterior-posterior (A), and medial-lateral (B) directions (gray arrow illustrates ground reaction force vector). In Whole body mechanics differ among running and cutting maneuvers in skilled athletes. Gait & posture, 42 (3), 240-245.

The magnitude of the cutting angle has been reported to alter the whole-body biomechanics and joint patterns during cutting. For instance, sharper cutting angles typically leads to a larger separation distance between the COM and COP. (Havens & Sigward 2015a). In addition, sharper angles require more deceleration and greater translation (Xu et al., 2004), whereas less sharper angles could be performed by slower running speeds, i.e. jogging or shuffling, before and after the directional change (Havens 2013, 7).

*Please note, that in the following chapters the term ‘deceleration’ is used the describe, for instance, the braking phase of running, since this term has become a commonly used word in the sport literature and among clinicians. However, the exact biomechanical term to describe the decrease in velocity would be ‘negative acceleration’ (Knudson 2003: 111).

3 OVERVIEW OF ANKLE AND KNEE INJURIES IN YOUTH TEAM SPORTS

There is no clear theoretical definition of an *injury,* since it's highly dependent of the context (Langley & Brenner 2004). In sports injury studies, however, definitions are helpful since they provide pragmatic or operational criteria for recording cases (Fuller et al., 2007). Fuller and colleagues (2007) defines an acute injury (occurring in rugby) as follows:

> "Any physical complaint, which was caused by a transfer of energy that exceeded the body's ability to maintain its structural and/or functional integrity, that was sustained by a player during a (rugby) match or (rugby) training, irrespective of the need for medical attention or time-loss from (rugby) activities. An injury that results in a player receiving medical attention is referred to as a 'medical-attention' injury and an injury that results in a player being unable to take a full part in future (rugby) training or match play as a 'time-loss' injury".

When further classifying injuries, several other factors should be considered – such as injury severity, location and the type of injury, whether the specific injury is a recurrent or first of a kind, and whether the injury occurred in training or during a match/competition. Another important factor regarding the injury classification is to describe the nature of the injury: whether the injury was a result of a contact with another player or object or was it 'noncontact' type. (Fuller et al., 2006; Fuller et al., 2007.)

Several studies (Fong et al., 2007; Borowski et al., 2008; Meeuwisse et al., 2003; Murphy et al., 2003; Räisänen et al., 2018) have demonstrated that in youth team sports the most injured body sites are ankle and knee, and the most frequent injury types consists muscle strains, ligament sprains, and contusions (Murhpy et al., 2003). For instance, findings from two recently published prospective cohort studies of young team sport athletes have demonstrated that among adolescent basketball players 78 % (Pasanen et al., 2017) and floorball players 81 % (Pasanen et., 2018) of the acute injuries affected the lower extremities, while majority of these injuries involved the joints or ligaments (54–67 %). Another well recognised finding is that in team sports greater amount of injuries have been found to occur in games than in practice (Ekstrand et al., 2011; Pasanen et al., 2017; Pasanen et al., 2018; Meeuwisse et al., 2003).

3.1 Ankle Injuries

3.1.1 The Structure and Functions of the Foot and Ankle

“The human foot is a masterpiece of engineering and a work of art”. This famous quote by Leonardo da Vinci (1452–1519), who himself was a passionate engineer and architect, describes, incisively, the complexity of the human foot. The foot and ankle system, indeed, is a sophisticated design composed of 28 bones, 33 joints, 112 ligaments, as well as 13 extrinsic and 21 intrinsic muscles (Altchek 2013: 11). The term ‘ankle’ is conventionally used to describe the talocrural joint: the articulation among the tibia, fibula, and talus. The term ‘foot’ consists all the tarsal bones (Figure 3), and the joints located distally to the ankle. Anatomically and functionally the foot is usually subdivided into the rearfoot, midfoot, and forefoot. Furthermore, the foot is characterized by three arches (anterior transverse arch, lateral longitudinal arch, medial longitudinal arch) (Figure 3). Every arch has its specific role, and together they compose a functional and coherent unit. (Neumann 2010: 573–618.)

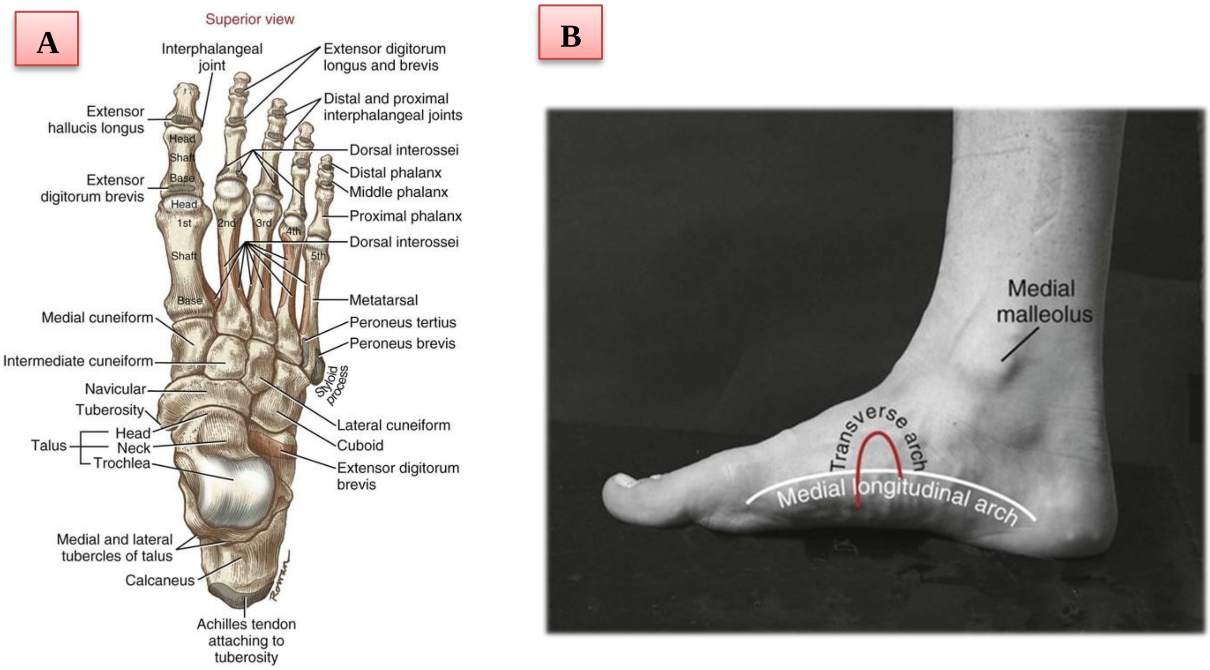

FIGURE 3. Neumann, D. A. 2010. Bones of the foot (A). Main arches of the foot (B): the medial longitudinal arch (white) and the transverse arch (red). In Kinesiology of the musculoskeletal system: foundations for rehabilitation (Figures 14-4 & 14-28). St Louis, MO: Mosby. Elsevier. Retrieved from https://musculoskeletalkey.com/structure-and-function-of-the-ankle-and-foot/#f0040.

Main Functions of the Foot. The foot is the only body part that is frequently in contact with the ground in many sports and, therefore, it should be able to adjust for the environment and perform many diverse dynamic functions (Chan & Rudins 1994; McPoil & Knecht 1985). During initial contact (e.g., walking or running) and mid-support phase, the foot attenuate impact loads and allow accommodation to uneven terrains. Therefore, the foot is often described as a mobile adaptor and an effective shock absorber. Furthermore, during the foot-strike and push-off, the foot should become a rigid lever to enable an effective motion towards to a desirable direction. (Chan & Rudins 1994; McKeon et al. 2015; McPoil & Knecht 1985.)

Motions of the Foot & Ankle. The ankle complex is composed of three joints, which enables different motions of the foot and ankle (Figure 4). *Tibiotalar joint* (also talocrural joint) is located between the distal ends of tibia and fibula and the superior aspect of the talus bone. This joint provides dorsiflexion (flexion of the foot in an upward direction) and plantarflexion (extension of the foot in a downward direction) movements occurring in the sagittal plane. *Subtalar joint* (also talocalcaneal joint) forms an articulation between the talus and calcaneus. Main movements provided about this joint are inversion (turning the sole of the foot inwards) and eversion (sole of the foot turns outwards) occurring in the frontal plane. *Transverse-tarsal joint* (also midtarsal joint or Chopart's joint) is shaped like 'S' and is composed by two joints: the *talonavicular* and *calcaneocuboid joints*. Calcaneocuboid joint forms an articulation between the calcaneus and cuboid, while the articulation of the talonavicular joint combines the talus and the navicular bone. This joint form a functional unit with the subtalar joint providing mainly inversion-eversion motions of the foot. (Brockett & Chapman 2016; Chan & Rudins 1994.) Additionally, most of the *abduction* and *adduction* movements of the foot (occurring in the transverse plane) is provided by transverse-tarsal and subtalar joints (Neumann 2010, 579). The movements of the foot and ankle are presented in Figure 4.

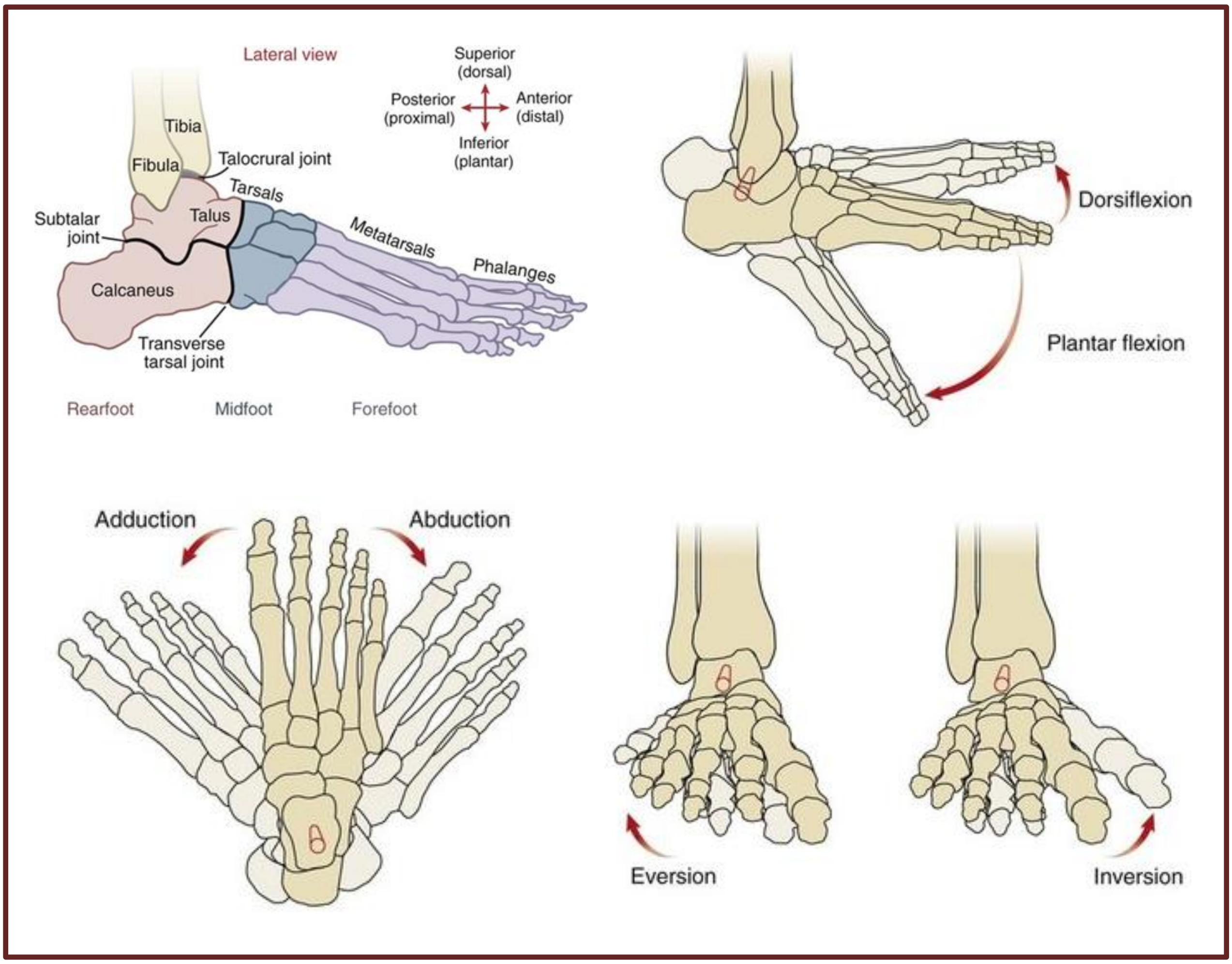

FIGURE 4. Neumann, D. A. 2010. Primary joints and motions of the foot. In Kinesiology of the musculoskeletal system: foundations for rehabilitation (Figure 14–1). St Louis, MO: Mosby. Elsevier. Retrieved from https://musculoskeletalkey.com/structure-and-function-of-the-ankle-and-foot/#f0040.

Triplanar Motions. It should be noted, that since the mechanical axes of the foot and the ankle doesn't run perpendicular to any of the cardinal planes, the movements created by the foot and ankle are practically described as *triplanar motions*. This could be interpreted, basically, that whenever you rotate the foot in any direction, there is always concurrent movements occurring in all cardinal planes. For instance, s*upination* and *pronation* (Figure 5) are three-dimensional motions created by the cooperation of the foot and ankle joints. Supination is a combination of plantarflexion, inversion and adduction of the forefoot. Pronation, on the other hand, is a combination of dorsiflexion, eversion and abduction of the forefoot. (Chan & Rudins 2004; Brockett & Chapman 2016.)

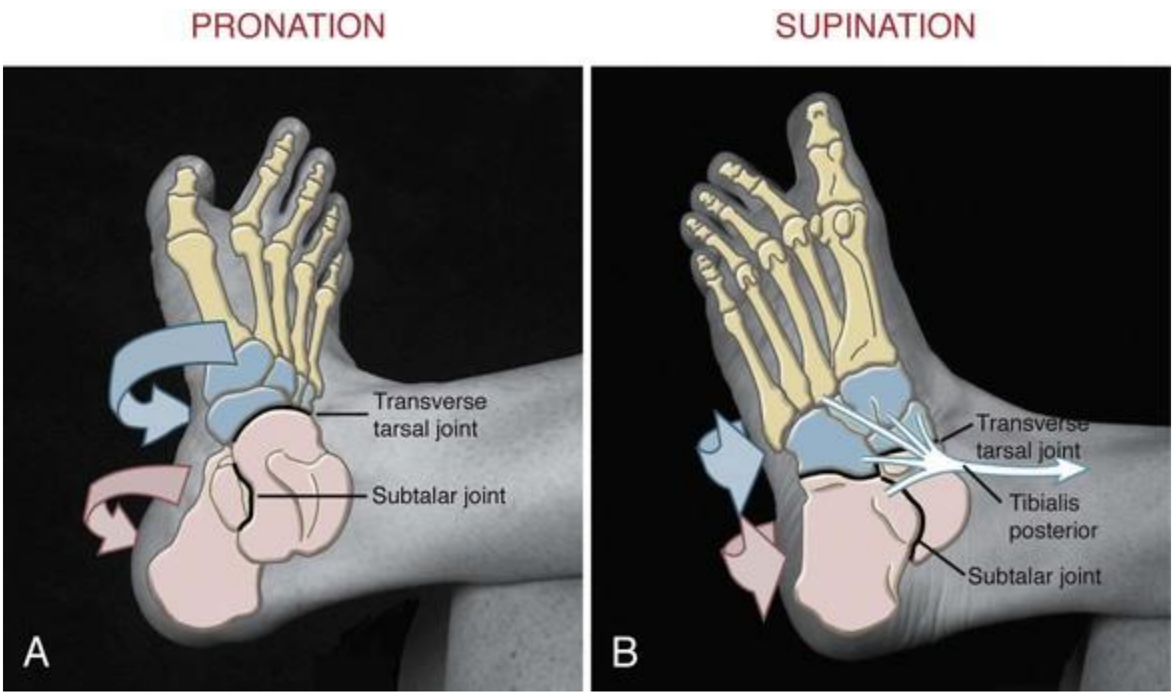

FIGURE 5. Neumann, D. A. 2010. Pronation (A) & supination (B) motions. In Kinesiology of the musculoskeletal system: foundations for rehabilitation (figure 14-26). St Louis, MO: Mosby. Elsevier. Retrieved from https://musculoskeletalkey.com/structure-and-function-of-the-ankle-and-foot/#f0040

Closed Chain Movements. Moreover, the movements described above need to be visualized as *open chain movements*, when the foot is off the ground and free to rotate. For instance, during gait or cutting manoeuvres or landing from jumps, when the foot is fixed to the ground ('closed chain'), the dorsiflexion and plantarflexion motions are defined differently: the forward rotation of the tibia towards the foot represent dorsiflexion (Figure 6), while the backward rotation of the tibia away from the foot illustrates plantarflexion. The dorsi- and plantarflexion angles, therefore, represents the angle between the tibia bone and the foot that is fixed on the ground. (Brockett & Chapman 2016; Neumann 2010, 582.)

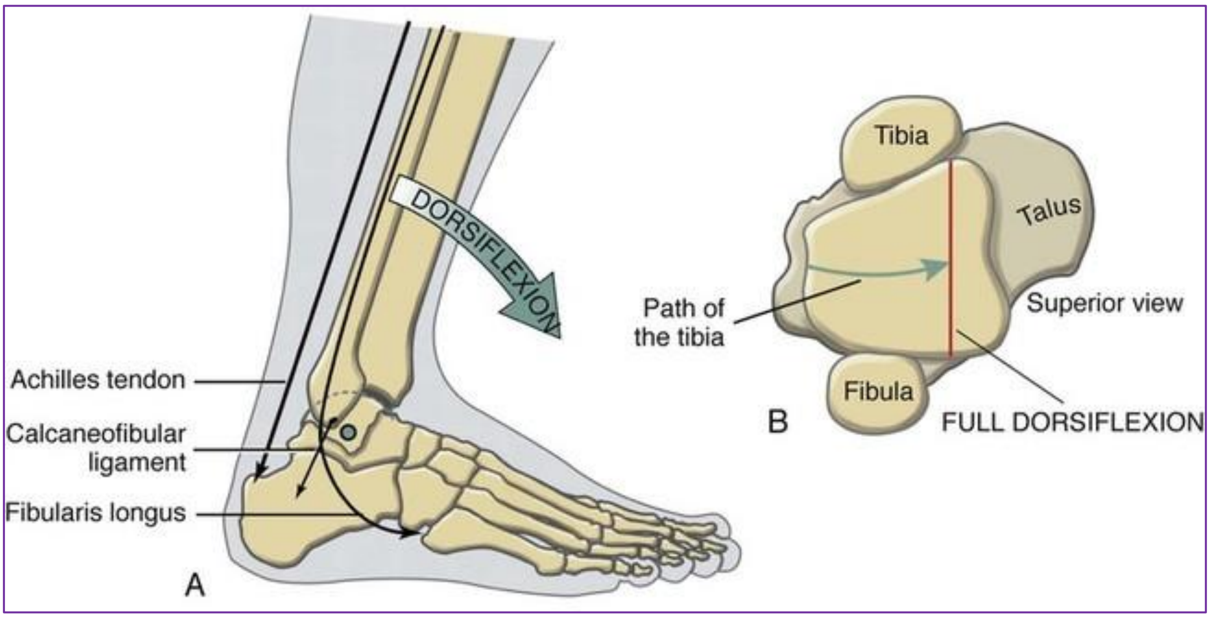

FIGURE 6. Neumann, D. A. 2010. Closed chain dorsiflexion. In Kinesiology of the musculoskeletal system: foundations for rehabilitation (figure 14-20). St Louis, MO: Mosby. Elsevier. Retrieved from https://musculoskeletalkey.com/structure-and-function-of-the-ankle-and-foot/#f0040

Alternative Terminology. A few deviant features regarding the foot and ankle movements should be highlighted. While inversion and eversion of the foot conventionally describes to medial and lateral rotation in frontal plane and about an anteroposterior axis, the foot adduction/abduction refer to the motion of the distal part (i.e., toes) of the foot in transverse plane and about a vertical axis (Neumann 2010, 583). The term “toe-in”, therefore, is often used to describe the adduction of the foot, while “toe-out” refer to the abduction of the foot. However, despite what is described in textbooks (Neumann 2010, 583) as abduction and adduction of the foot, is often substituted with the terms “internal/external” rotations of the foot (Chan & Rudins 2004). Additionally, terms inversion and supination, as well as eversion and pronation, are sometimes used as synonyms (Chan & Rudins 2004).

The Ligamentous Structure of the Ankle. The ankle structure is composed of three groups of ligaments: *the lateral ligaments*, *the deltoid ligaments* and the *syndesmosis complex* (i.e., ligaments above the ankle joint) (Figure 7). Together they spread around the ankle, across multiple joints and operate as static stabilizers, resisting both excessive eversion and inversion of the ankle. (Neumann 2010, 580–581; Peterson & Renström 2016, 501.)

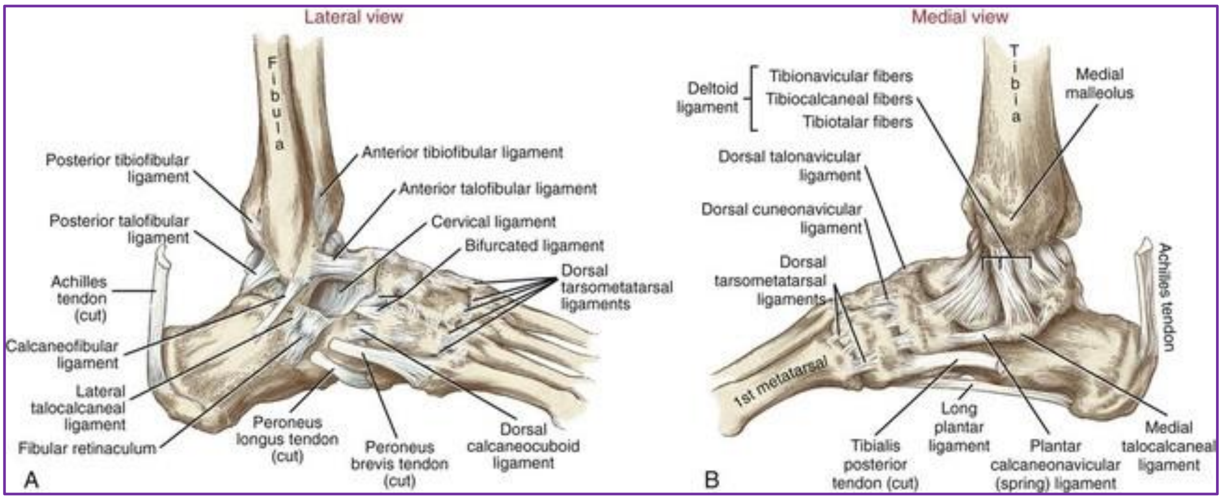

Figure 7. Neumann, D. A. 2010. Lateral (A) and medial (B) view of the ligaments of the ankle. In Kinesiology of the musculoskeletal system: foundations for rehabilitation (figures 14-14 & 14-15). St Louis, MO: Mosby. Elsevier. Retrieved from https://musculoskeletalkey.com/structure-and-function-of-the-ankle-and-foot/#f0040

Lateral Ligament Complex. The lateral ligament complex of the ankle consists three ligaments: *the anterior talofibular ligament* (ATFL), *the calcaneofibular ligament* (CFL) and *the posterior talofibular ligament* (PTFL) (Neumann 2010, 581). These ligaments function as a unit, so that they often act synergistically to limit some precise motion, however, the position of the foot determines which of the ligaments acts as the primary stabilizer (Peterson & Renström 2016, 501). Therefore, lateral ligaments, due to their anatomical position and shared functions, are often injured in combination (Neumann 2010, 581; Peterson & Renström 2016, 502).

ATFL is anatomically close to parallel with the longitudinal axis of the foot. The ligament strain increases as the foot plantarflexes and anatomically it becomes nearly parallel with the longitudinal axis of the tibia (Figure 8). Main function of the ATFL is to resist ankle inversion. It is the weakest of the ankle ligaments and, therefore, injured often in the inversion ankle sprains. (Peterson & Renström 2016, 501.)

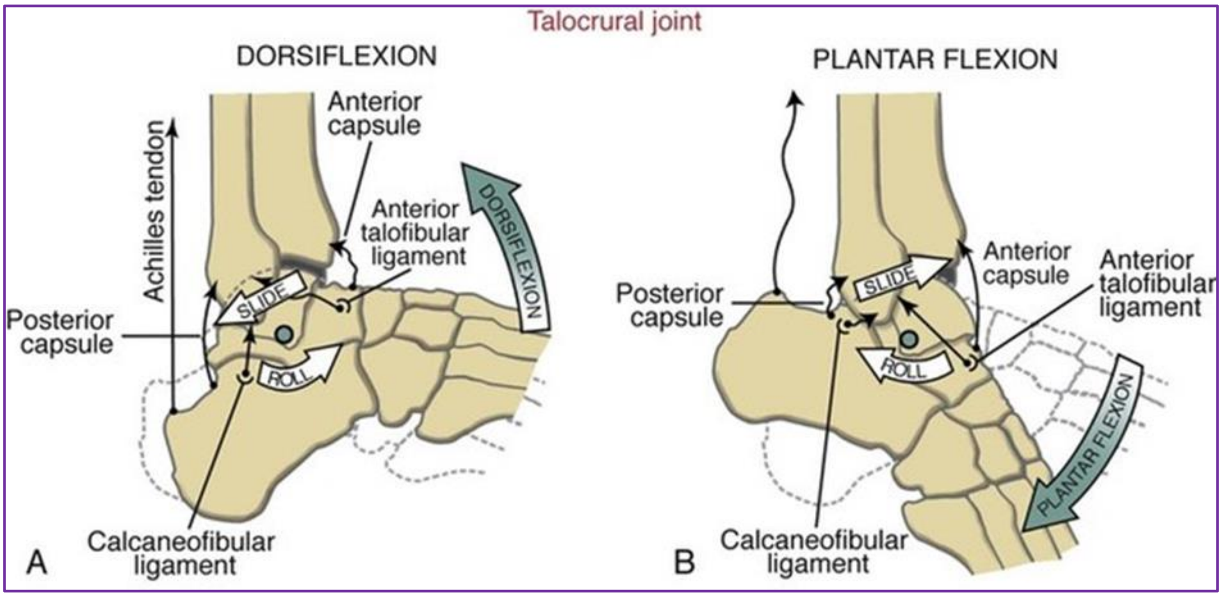

FIGURE 8. Neumann, D. A. 2010. Lateral view of the ankle illustrating the stretched (elongated arrows) and slackened structures (wavy arrows) during talocrural joint during dorsiflexion (A) and plantar flexion (B). In Kinesiology of the musculoskeletal system: foundations for rehabilitation (figure 14-18). St Louis, MO: Mosby. Elsevier. Retrieved from https://musculoskeletalkey.com/structure-and-function-of-the-ankle-and-foot/#f0040.

When the foot is in neutral position **CFL** is oriented nearly parallel with the longitudinal axis of the tibia. It contributes lateral stability by resisting inversion across the talocrural and subtalar joint of the ankle. (Neumann 2010, 581; Peterson & Renström 2016, 501.) When the foot is fully dorsiflexed CFL resists, particularly, inversion across the talocrural joint (Neumann 2010, 581). During plantarflexion, this composition changes as the CFL becomes almost perpendicular in relation to the fibula, while providing less stability for the ankle (Figure 8) (Peterson & Renström 2016, 501). **PTFL** originates from the lateral malleolus and attaches distally to the talus. Its primary function is to prevent the talus to move posteriorly in relationship to the fibula (Peterson & Renström 2016, 501) and, additionally, to limit excessive abduction of the talus, particularly, when the ankle is fully dorsiflexed (Neumann 2010, 582).

The fan-shaped **deltoid ligament** is a strong and broad ligament on the medial side of the ankle. The ligament is composed of two, deep and superficial, layers. (Neumann 2010, 580.) The deltoid ligaments primary function is to resist the eversion across the talocrural, subtalar, and talonavicular joints (Neumann 2010, 581) and, additionally, to prevent the anterior and posterior displacement of the talus (Peterson & Renström 2016, 501). The **syndesmotic**

ligament complex provides stability between the distal tibia and the fibula (i.e., binds the distal tibia and fibula together). It is composed of three ligaments: the anterior tibiofibular ligament, the posterior tibiofibular ligament, and the interosseous tibiofibular ligament. In addition, the inferior segment of the interosseous membrane assists to stabilize the tibiofibular syndesmosis. (Golano et al., 2010.) *As a side note, inferior transverse tibiofibular ligament is in some textbooks considered as a separate ligament (Peterson & Renström 2016: 501) while, generally, this is considered as a part of the posterior talofibular ligament (Golano et al., 2010; Neumann 2010: 582).

3.1.2 Classification of Ankle Sprains

Various grading systems have been utilized to grade an acute ankle ligamentous sprain injury (Fong et al., 2009a). For instance, ankle sprains (i.e., injury to the ankle ligaments), may be classified based on the **injury mechanism** and further divide into **grade I, II** or **III** depending on the severity of the injury (Peterson & Renström 2016, 502; Wolfe et al., 2001). The grade I sprain has only a ligament stretch without tearing (Peterson & Renström 2016: 502) or a partial tear of a ligament (Wolfe et al. 2001) combined with minor or no functional loss; the grade II sprain consists incomplete tear of a ligament with mild to moderate loss of motion and function, and grade III sprain is characterized by a complete rupture of a ligament associated with loss of instability of a ligament (Chinn & Hertel 2010; Peterson & Renström 2016, 502; Wolfe et al. 2001).

Depending on the mechanism of injury the sprain might occur to the **lateral aspect** (ATFL & CF-ligaments) of the ankle, **medial aspect** of the ankle (the deltoid ligaments) or to the **syndesmosis** (high ankle sprain), i.e. the tibiofibular ligaments and the interosseus membrane, (Chinn & Hertel 2010; Peterson & Renström 2016, 502–510). The prevalence and incidence of these different sprains are discussed in the next subchapter (3.1.3), while the biomechanical risk factors and specific injury mechanisms are presented in chapters 3.1.4 and 3.1.5.

3.1.3 The Prevalence and Incidence of Ankle Injuries

The Prevalence and Incidence. Findings from a systematic review conducted by Fong and colleagues (2007) showed that among 70 investigated sports, the ankle was the most injured body site in most sports (24 sports, 34.3%). In addition, Hunt and colleagues' (2017) prospective study demonstrated that among elite collegiate athletes the prevalence of foot/ankle injuries were, as much as, 27% of total musculoskeletal injuries. Moreover, the results from two prospective follow-up studies (Pasanen et al., 2017; Pasanen et al., 2018) establishes the previous findings by reporting high acute ankle injury prevalence (37–48 %) and injury rates in junior floorball (IR 9.56; 95% CI 5.49–13.63) and adolescent basketball players (IR 15.05; 95% CI 9.79-20.31) per 1000 game hours.

Injury Location. Fong and colleagues (2007) reported that the most frequent ankle injury type in most sports was the ankle sprain (33 of 43 sports, 76.7%), accompanied with fracture (7 sports, 16.3%). In sports such as basketball, indoor volleyball and indoor soccer ankle sprains comprehended more than 80% of all ankle injuries (Fong et al., 2007). Furthermore, results from another systematic review composed by Doherty et al., (2014) elaborates that the three most common types of ankle sprains are lateral ankle sprain, syndesmotic (high) ankle sprain and deltoid (medial) ligament sprain, respectively. Previous studies have demonstrated, for instance, that among male soccer players (Walden et al., 2013), NCAA–athletes (Roos et al., 2017) and basketball players (McGuine et al., 2000) the lateral sprains comprised, as much as, 51%, 73.9 % and 86.9 % of all reported ankle sprains, respectively. There is two main reasons why the ATFL is the one getting injured the most: partially due to its anatomical location, but also because it's the weakest ligament of the lateral aspect of the foot (Fong et al., 2009a). While an isolated ATFL tear is clearly the most common ankle injury, in 20% of the cases there is a combination of injury, where both ATFL and CFL suffers a tear (Peterson & Renström 2016, 502).

3.1.4 The Injury Mechanism Associated with Ankle Injuries

Bahr & Krosshaug (2005) emphasizes that, in addition of establishing the risks factors for injury, it is equally important to recognize the *injury mechanism* (i.e., how injuries happen) to innovate and promote successful prevention/reduction interventions associated with specific sport injuries. The term 'injury mechanism', as Bahr and Krosshaug notifies, is generally used in the literature, but the meaning of it hasn't been well defined. They argue that:

> "a complete description of the mechanisms for a particular injury type in a given sport needs to account for the events leading to the injury situation (playing situation, player and opponent behaviour), as well as to include a description of whole body and joint biomechanics leading up to, and at the time of injury."

Considering the aforementioned, 'injury mechanism' is here defined, analogously to Bahr and Krosshaug (2005), as follows: a) narration of the sport specific circumstances where injuries occur, b) description of player's action and interaction with the opponent, c) narrative of whole body mechanics, and c) description of joint/tissue biomechanics that leads to a mechanical load in excess which can't be tolerated, and which eventually leads to an injury. The circumstances related to ankle injuries are viewed more precisely in the next paragraph, while the back end of this section consists a detailed description of specific biomechanics associated with ankle injuries. As highlighted above, lateral ligament sprains comprehend almost all non-contact ankle ligament injuries in sports while it is, furthermore, by far most studied acute ankle injury subtype. Therefore, a closer look is, particularly, placed on the mechanisms related to lateral sprains.

Injury Circumstances. Several studies have investigated the injury circumstances associated with ankle injuries in various sports (Cumps et al., 2007; Meeuwisse et al., 2003; Roos et al., 2017; Walden et al., 2013). For instance, Cumps and colleagues (2007) suggested that in basketball the two most common circumstances for an acute ankle sprain is landing on an opponent's foot or rapid change in directions, respectively. Furthermore, McKay and colleagues (2001) also highlighted that a high percentage of acute ankle injuries occurred while landing (45%) – with half of these injuries occurring due to landing on another athlete's foot, and another half as result of landing on the court surface (30%). In addition, the findings from Pasanen and colleagues (2017) showed that 47% of ankle ligament injuries in adolescent basketball and 77 % in junior floorball players (Pasanen et al., 2018) resulted via noncontact and indirect injury mechanisms. Notably, in floorball the direction chance/sudden stop was reported as the most frequent injury situation (21% of all injuries) (Pasanen et al., 2018)

Traditionally Suggested Injury Mechanism. Previous studies have proposed that the biomechanical ankle joint/tissue mechanism for lateral sprain injury involves inversion and internal rotation of the forefoot (Safran et al., 1999) and plantarflexion with the subtalar joint adducting and inverting (Vitale 1988). Over 40 years ago Garrick (1977) described that the lateral ankle sprain typically results from a motion pattern including inversion, internal rotation of the forefoot and plantarflexion. Furthermore, a 'Position Statement of the International Ankle Consortium' paper (Gribble at al. 2014), from a few years back, endorsed the definition of lateral ankle sprain as "a result of excessive inversion of the rear foot or a combined plantar flexion and adduction of the foot". To underpin these hypothesizes and definitions, both cadaveric (Bahr et al., 1998) and muscle model driven computer simulations (Wright et al., 2000) studies have suggested that the inversion, particularly, is a vulnerable position for the ankle as the ATFL acts as the primary restrain in that motion (Figure 9). Anatomically viewed, the ATFL ligament tightens in plantar flexion (Bahr et al., 1998), likewise in internal rotation of the forefoot (Fong et al., 2012) and, therefore, excessive plantar flexion or internal rotation of the forefoot on an inverted ankle could cause a rupture of the ATFL (Bahr et al., 1998). Skazalski and colleagues (2018) emphasizes, that what Garrick proposed decades ago, is still considered as the traditionally suggested mechanism for lateral sprain injury. Verification for this argument could be found from the current sport literature (Valenzuela et al., 2016; Gehring et al., 2013; Peterson & Renström 2016, 502).

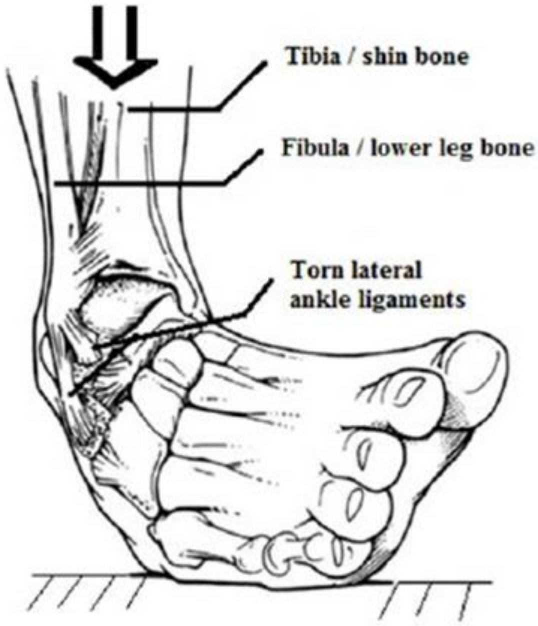

FIGURE 9. Alcocer et al. 2012. Traditionally suggested mechanism for lateral ankle sprain involves foot inversion and internal rotation of the forefoot. In Major trends in the development of ankle rehabilitation devices. Dyna, 79 (176), 45-55.

Help of the New Technology. The rapid evolution of sport biomechanics techniques has enabled the emergence of numerous different methodological approaches, which have helped to deepen the understanding, for example, about the precise ankle joint mechanism that may lead to injury (Krosshaug et al., 2005). Some of these approaches have included video recording analysis of actual injury situations and 3D–laboratory motion analysis (Fong et al., 2012; Gehring et al., 2013; Kristianslund et al., 2011; Mok et al., 2011). For instance, studies have investigated the precise timeline of the injury. Based on the results it has been suggested that the actual injury occurs 105–180ms after the initial contact (where the maximum inversion angle is obtained) and, also, when the loads are likely to exceed injury threshold (Gehring et al., 2013; Kristianslund et al., 2011; Mok et al., 2011). Furthermore, the new findings have added knowledge to the current understanding, while also generating new theories in respect of the ankle joint biomechanics during inversion sprain injury (Fong et al., 2009b; Kristianslund et al., 2011; Mok et al., 2011). These findings will be discussed next.

Dorsiflexion During Injury. Some of the contrasting findings with respect to the 'traditionally suggested mechanism' were reported by two researcher groups (Fong et al., 2009b;

Kristianslund et al., 2011), whom demonstrated similar results in almost identical study settings. In both studies, an athlete (basketball & handball player) suffered an accidental ankle sprain while performing a sidestep cutting in a motion analysis laboratory. Kinematic data from both cases demonstrated, not surprisingly, that peak inversion and excessive internal rotation of the foot was detected at the time of injury. The interesting finding, however, was that the ankle was in a dorsiflexed position while the injury, supposedly, occurred. Additionally, two other studies that utilized model-based image-matching of injury videos from tennis (Fong et al., 2012) as well as from high jumping and field hockey (Mok et al., 2011), demonstrated that the ankle sprain injury resulted from a motion combination of foot internal rotation and inversion, while the ankle was either in a neutral or dorsiflexed position. Furthermore, recent video analysis studies from volleyball (Skazalski et al., 2018) and basketball (Panagiotakis et al., 2016) also supports the previous findings, suggesting that landing-related injuries occur as a result of rapid inversion, without the presence of any significant plantarflexion. Skazalski and colleagues (2018) points out that in typical landing related injury situation, the ankle is in plantarflexion at initial contact and then starts dorsiflexing towards a foot flat position on the ground. They also emphasize, that in most injury situations inversion is absent until the ankle reaches at least the neutral position.

The New Paradigm. The most recent 'International Ankle Consortium statement' paper (Delahunt et al., 2018) has a slightly different approach compared to the previous paper regarding the definition of acute lateral ankle sprain. The lateral sprain is still described as an inversion and internal rotation combination injury; however, this paper declares that the injury could occur, in fact, irrespective to the sagittal plane motion – i.e., either in plantarflexion or dorsiflexion. In summary, foot inversion is suspected to be the key factor for lateral ankle sprain while internal rotation loading of the foot, furthermore, should be considered as another essential component (Delahunt et al., 2018). Opinions are, however, divided on what is the role of the sagittal plane motions during the injury situations. While some studies suggest that during cutting task related injuries the ankle is either in dorsiflexion or close to neutral position (Fong et al., 2012; Kristianslund et al., 2011; Mok et al., 2011), other studies (Gehring et al., 2013) indicates that these injuries may also happen when the foot is in a plantarflexed position. Clearly, more studies with respect to the lateral sprain injury mechanisms are required.

3.1.5 Risk Factors Associated with Ankle Injuries

The injury, mainly regardless of the nature of it, is essentially an outcome of a chain reaction involving various and complementary circumstances (Figure 10) (Meeuwisse et al., 2007). Previous studies have evaluated extrinsic risk factors (those outside of the body) and intrinsic risk factors (those from within the body) that may associate with ankle injuries (Beyonnen et al., 2003; Fong et al., 2009a; Murphy et al., 2003; de Noronha et al., 2006). The essence of risk factor identification is to enable optimal implementation of injury prevention strategies by considering how internal and external risk factors might modify the risk of injury (Beyonnen et al., 2002; de Noronha et al., 2006; Murphy et., 2003; Krosshaug et al., 2005).

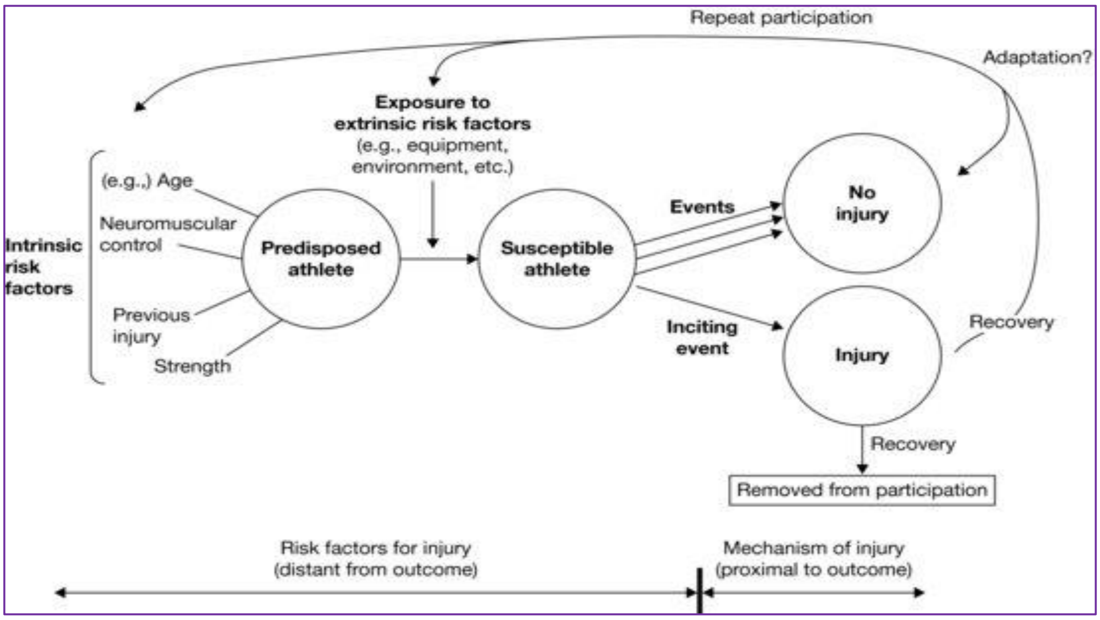

FIGURE 10. Meeuwisse, W. H., et al. 2007. A dynamic, recursive model of etiology in sport injury. In Clinical Journal of Sport Medicine, 17 (3), 215-219.

Largely, the literature seems to be very divided in respect of the causality, and its magnitude, to many of these risk factors related to ankle injuries (Beyonnen et al. 2002; de Noronha et al. 2006; Murphy et al. 2003). Furthermore, Fong and colleagues (2009a) emphasizes that these risk factors only adduce some correlation with ankle sprains, hence those should be only deliberately considered as direct cause of injuries. Despite some contradictory findings, the general agreement indicates the following: a) the rate of injury is greater in competition than in training sessions, b) the risk of injury is increased when playing on artificial turf compared to grass or gravel, c) previous injury, when combined with inadequate rehabilitation, is a risk factor for subsequent injury. (Murphy et al., 2003.) Furthermore, some evidence indicates that female sex and young age (Doherty et al., 2014), as well as intrinsic functional deficits, such as higher postural sway, lower postural stability, lower inversion proprioception, higher concentric plantar flexion strength at faster speeds and lower eccentric eversion strength at slower speeds (Witchalls et al., 2012) could be associated with higher rate of ankle injuries. The risk factors, which are mainly highlighted in the literature, are presented in Tables 1 and 2.

TABLE 1. Potential Intrinsic Risk Factors for Ankle Injuries.

	Individual Features		**Functional Deficits**		
Risk Factor	Notes		Notes		
Sex	No association between sex and injury [1,2]. Higher incidence of ankle sprain in females than males [3]		**Previous injury**	Previous injury in conjunction with inadequate rehabilitation is a risk factor for re-injury of the same type and location [1]. Previous sprain with inadequate rehabilitation	
Age	Contradictory findings[1]. Higher incidence of ankle sprains in children compared with adolescents, and in adolescents compared with adults [3]		**Ankle dorsiflexion ROM**	Not a risk factor [1, 2, 5]. Decreased dorsiflexion range of motion is a potential risk factor [4].	
Body size	Contradictory findings [1, 2]		**Ankle muscles strength**	Contradictory findings [1, 2]. Potential risk factor [5].	
Anatomical alignment	Contradictory findings [1, 2]		**Ankle muscles reaction time**	Contradictory findings [1, 2]. Not a risk factor [5].	

Foot morphology/ foot type	No association between foot type and injury [1, 2]		**Poor aerobic fitness**	Potential risk factor [1].	
Generalized joint laxity & ankle-joint laxity	Generalized joint laxity is not a risk factor [1, 2]. Contradictory findings of ankle-joint laxity [1, 2]		**Postural sway/balance**	Contradictory findings [1, 2]. Potential risk factor [4, 5]	
Limb dominance	Contradictory findings [1, 2]				

[1] Murphy et al. 2003, [2] Beyonnen et al. 2002 2, [3] Doherty t al. 2014 3, [4] de Noronha et al. 2006, [5] Witchalss et al. 2012.

TABLE 2. Potential Extrinsic Risk Factors for Ankle Injuries.

Risk Factor	Notes
Level of competition	Incidence of injury is higher during games than practice [1, 2]
Skill level	Contradictory findings [1]
Shoe type	Contradictory findings [1]
Playing surface	Increased incidence on turf compared with grass or gravel [1]
Ankle brace/taping	The use of ankle tape or brace decreases the incidence of ankle injury [1, 2]

[1] Murphy et al. 2003, [2] Beyonnen et al. 2002 2, [3] Doherty t al. 2014 3, [4] de Noronha et al. 2006, [5] Witchalss et al. 2012.

3.2 Knee Injuries

3.2.1 Ligamentous Structure and Functions of the Knee

The knee joint combines the thigh bone (femur) to the shin bone (tibia). In addition, knee joint involves two other bony structures: fibula (located on the lateral side of tibia) and kneecap (patella). Quadriceps tendon and patellar tendon joins the four-headed thigh muscle (quadriceps) to the tibia. This muscle extends the knee joint, while patella contributes some biomechanical advantage to enhance this motion. (Neumann 2010, 520–522.)

Functions of the Knee. Tibiofemoral knee joint motions occur in three planes (sagittal, frontal and transverse) (Figure 11). These motions consist flexion and extension (in the sagittal plane), abduction and adduction (in the frontal plane), as well as internal and external rotation (in transverse plane). Furthermore, translations could occur in the knee joint: anteriorly and posteriorly (in the sagittal plane), medially and laterally (in the frontal plane), and compression and distraction (transverse plane). (Quatman et al., 2010.)

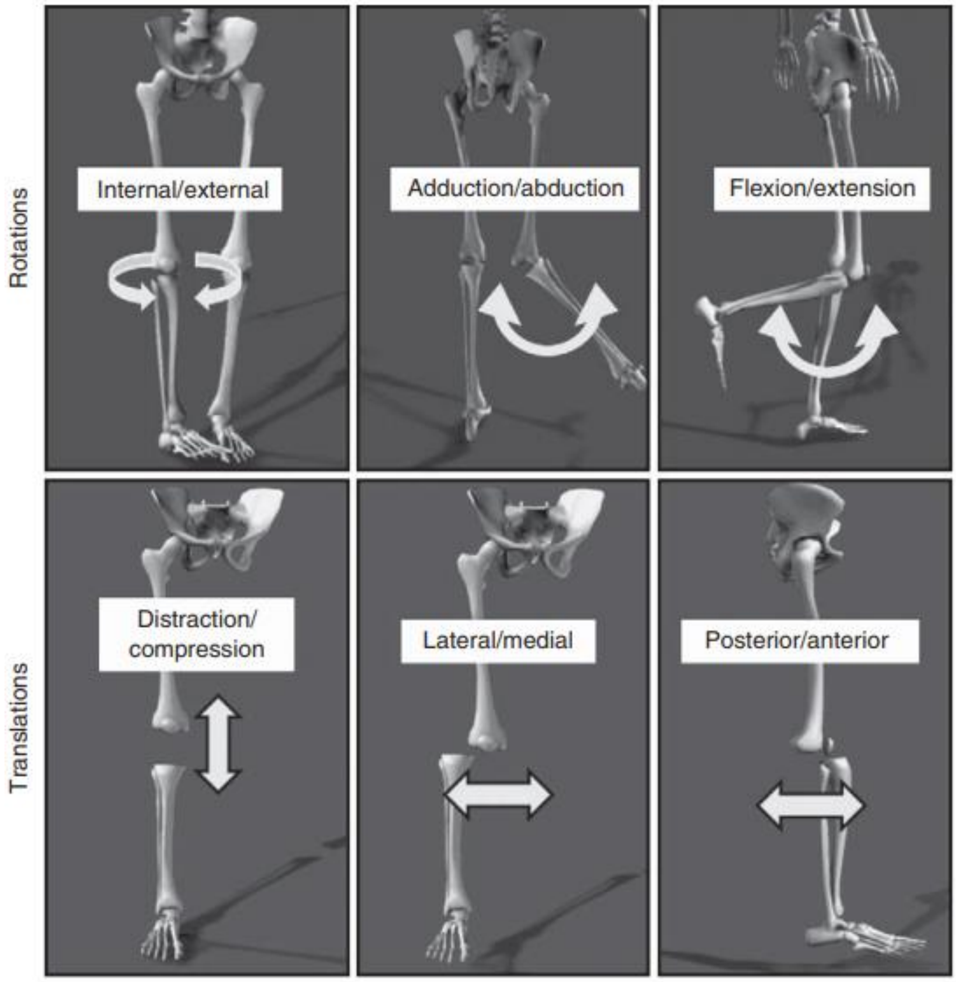

FIGURE 11. Quatman, C. E., et al. 2010. Rotation and translation motions of the knee joint. In A 'plane' explanation of anterior cruciate ligament injury mechanisms. Sports Medicine 40 (9), 729-746.

Knee Ligaments. Four solid ligaments compose a structure around the knee joint and provides stability to the knee (Figure 12 & Figure 13). The functions of the *medial collateral ligament* (MCL) and the *lateral collateral ligament* (LCL) is to prevent the femur gliding side-to-side. Additionally, *anterior cruciate ligament* and *posterior cruciate ligament* reduces the abnormal forward/backward sliding of femur and tibia in relation to each other. The function on these two ligaments is to prevent hyperextension, hyperflexion and abnormal rotation of the knee joint. (Peterson & Renström 2016, 398.) The *medial* and *lateral menisci* locate between the femur and tibia. These C-shaped pieces of cartilage function as shock absorbers during, both relatively low and rapid loading rates. (Peterson & Renström 2016, 426.)

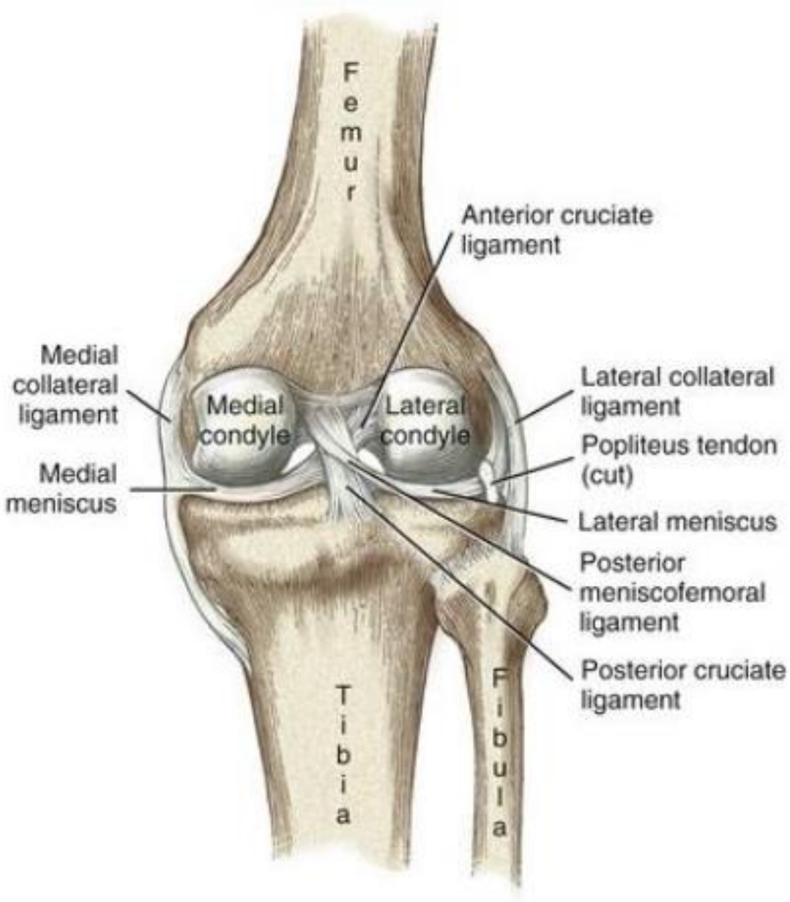

Figure 12. Neumann, D. A. 2010. Posterior view of the knee ligamentous structure. In Kinesiology of the musculoskeletal system: foundations for rehabilitation, ed 2 (Figure 13–12). St Louis, MO: Mosby. Elsevier.

ACL. The primary function of the ACL, which connects the femur to the tibia, is to provide passive restraint against anterior tibial translation with respect to the femur (Domnick et al., 2016; Kiapour et al., 2014). Moreover, it has been widely suggested that ACL stabilizes the internal rotation of the knee (Domnick 2016; Kiapour et al., 2014; Markolf et al., 1995; Peeler et al., 2017; Zantop et al., 2006), yet the clinical relevance of this claim should be further investigated (Amis 2012). Anterior tibial translation is minimal when the knee is close to extension, however, as the knee reaches a flexion alignment between 15° and 40° the translation increases and, therefore, ACL needs to provide enough restrain against excessive tibial translation (Domnick et al., 2016). Furthermore, it has been also demonstrated that ACL plays a significant role in restraining the varus-valgus motion of the knee joint (Markolf et al., 1984; Ohori et al., 2017).

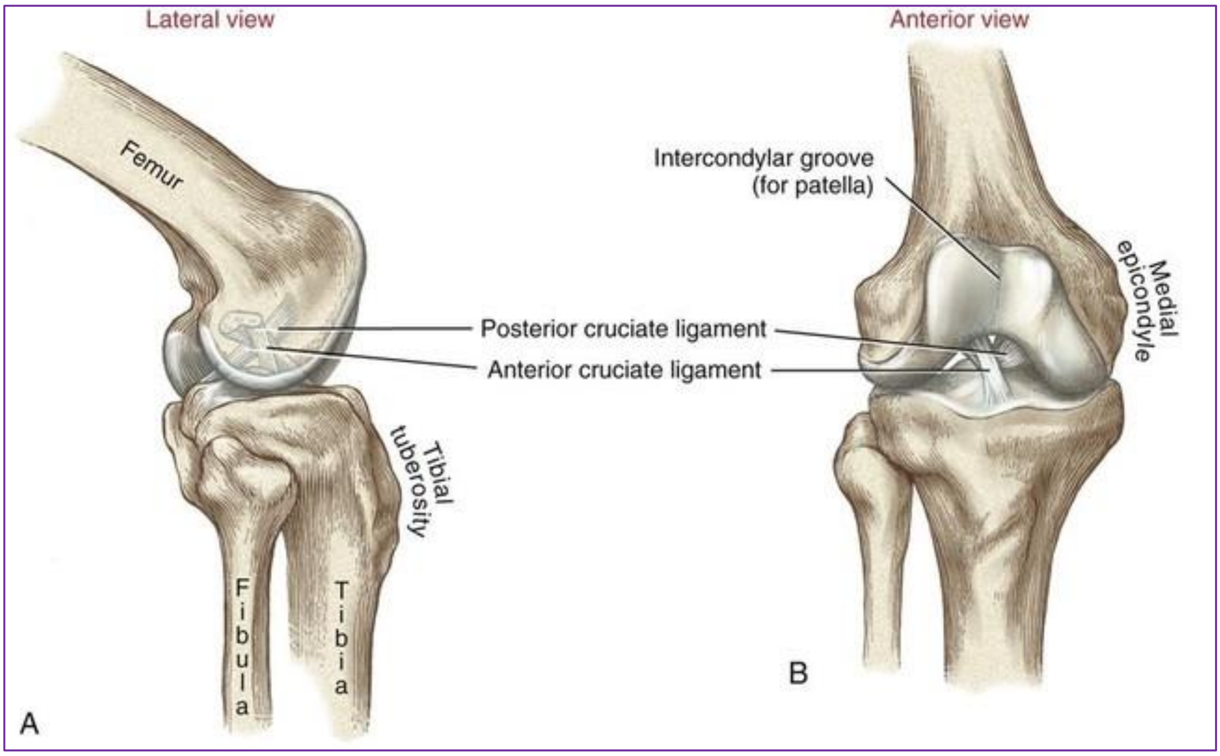

Figure 13. Neumann, D. A. 2010. Lateral (A) & anterior (B) view of the anterior and posterior cruciate ligaments. Kinesiology of the musculoskeletal system: foundations for rehabilitation, ed 2 (Figure 13-19). St Louis, MO: Mosby. Elsevier.

Internal & External Rotations. These rotational motions of the knee should be further explained, since the precise understanding of the terms are considered important and can cause confusions (Neumann 2010: 530). 'Tibial-on-femoral rotation' describes in which way the tibia bone is rotating (externally or internally) in relation to the stationary femur. 'Femoral-on-tibial rotation' describes, vice versa, the femur bone rotation in relation to the stationary tibia. However, when describing the rotation of the *knee joint* (not just bony rotation), a simple rule is followed. Neumann (2010, 530) describes this rule as follows: "axial rotation of the knee is based on the position of the tibial tuberosity relative to the anterior distal femur". For instance, external rotation occurs when, by the result of the movement at the knee joint, the tibial tuberosity is located laterally compared to the distal anterior femur. Internal rotation, conversely, occurs when the tibial tuberosity is located medially in relation to the distal anterior femur. The direction of the knee joint rotation is, consequently, opposite to the movement of the femur: external rotation of the knee takes place when the femur rotates internally, and internal rotation of the knee occurs because of external rotation of the femur. (Neumann 2010, 529–530.) Due to the complexity of these rotational movements, it is important, therefore, to clearly describe the precise kinematics of the tibia and femur while illustrating motions of the knee joint. Just simply using the terms, such as ‘internal rotation of the leg” or ‘external rotation of the lower limb” could lead to misinterpretations.

3.2.2 Classification of Knee Injuries

The injury to the knee can occur, in isolation, to any of the components of the knee: bones (e.g., fractures, dislocations), cartilage (e.g., meniscus injuries), ligaments, tendons (e.g. tendinopathies) and bursas. Furthermore, ligament tears or menisci lesions can occur in combination with other ligament/menisci or, at worst, concurrently with a fracture or tendon rupture. (Peterson & Renström 2016, 397–461.)

Knee ligament injuries are classified into three grades, according to the severity of the injury. The grading system is analogous to ankle injury classification – Grade I: microstructure; Grade II: partial tear; Grade III: a complete tear – (Peterson & Renström 2016, 399). See chapter 3.1.2 (p. 17) for more information about the injury classification.

3.2.3 The Prevalence & Incidence of Knee Injuries

Prevalence and Incidence. Among 70 different sports, knee was found to be the second most injured body site after ankle (14 sports, 20.0%) (Fong et al., 2007). The prevalence of knee injuries is particularly high in pivoting court, field and indoor games (Fong et al., 2007; Shea et al., 2004). The findings from a comprehensive 10-year epidemiology study, conducted by Majewski and colleagues (2006), showed that almost 40% of all sports related injuries affected the knee. Furthermore, knee injuries are found to account 15 % of all high school sport injuries (Ingram et al., 2008; Swenson et al., 2013), 15 % of all injuries among adolescent basketball athletes (Pasanen et al., 2017), and 18% of all injuries among junior floorball players (Pasanen et al., 2018). Additionally, Pasanen and colleagues (2017) calculated high injury rates among junior floorball players (IR 7.74, 95% CI 4.08–11.41) and adolescent basketball athletes (IR

6.80, 95% CI 3.25-10.34) per 1000 game hours, while they also demonstrated that 44% of all knee injuries were severe, resulting time loss from sports more than 28 days.

Injury Type. One of the merits of studies such as Majewski et al. (2006) and Swenson et al. (2013) is that these studies classified the athletic knee injury types. Both studies showed similar results indicating that *ligament sprains* accounts 44.8–48.2 % of all knee injuries, whereas contusions, cartilage lesions, dislocations, fractures, tendon injuries and muscle injuries are substantially less common. Both studies showed that *ACL* was an involved structure in 20.3%–25.4% of all knee injuries cases, while *menisci* injuries accounted for 14.5%–23%, *medial collateral ligament* (MCL) injuries 7.9%–36.1%, *lateral collateral ligament* (LCL) injuries 1.1%–7.9%, and *posterior cruciate ligament* (PCL) injuries 0.65%–2.4% of all knee injuries. While the literature (Peterson & Renström 2016, 401) recognises ACL injuries as the most common ligament injury to the knee joint, Roach et al. (2014) emphasizes MCL injuries are relatively common in young athletes in certain sports (e.g., soccer & rugby). In addition, it should be further noted, that MCL and medial meniscus are often injured in combination with the ACL: MCL in 20% of the ACL cases, while medial meniscus up to 90% of the ACL cases (Domnick et al., 2016).

3.2.4 Injury Mechanism Associated with Knee Injuries

The term *injury mechanism* has been defined previously on Chapter 3.1.4. Like ankle injuries, specific knee injuries are derived from different injury mechanisms – and are also naturally dependent of the type of sport being played. For instance, of all MCL and PCL injuries in soccer, 70% were due to contact with another player or an object, whereas *only* 37% of ACL injuries resulted from a contact situation (Lundblad et al., 2013). In line with these results, it has been proposed that approximately 70–80% of the ACL injuries occur in *noncontact* rapid playing situations, such as single-leg landings and rapid cutting manoeuvres combined with sudden deceleration motion (Boden et al., 2000; Cochrane et al., 2007; Weiss et al., 2015). From a biomechanical standpoint, previous studies have reported that during change of direction, for instance, the loads are multiple times higher compared with straight-line running, thus placing the knee structures more vulnerable position for injuries (Brown et al., 2014).

Anterior crucial ligament injury prevention is considered as a hot topic in the field of today's sport injury research (Webster & Hewett 2018; Valenzuela et al., 2016) – while it has also been one of the most studied structures of the human musculoskeletal system over the past decades (Kiapour et al., 2014). Several studies have described the biomechanics associated with ACL injuries (Bencke et al., 2013; Fox et al., 2014; Hewett et al., 2005; Sugimoto et al., 2015). While in the present study the interest is not only to investigate the kinematic factors related to ACL injuries, but rather, collect the data with respect to *all* non-contact knee ligaments injuries, considering the nature of other knee injuries, it's rational, in this chapter, to focus on findings describing the biomechanical risk factors related to ACL injuries.

In the literature, the term 'dynamic knee valgus' or 'valgus collapse' is often used as a synonym to knee abduction. Hewett and colleagues (2005) have defined the dynamic valgus as the "position or motion of the distal femur toward and distal tibia away from the midline of the body" (Figure 14). Female athletes, particularly, who represent increased valgus collapse and high knee abduction loads are suggested to be at increased risk of ACL injury (Hewett 2005). Previous studies, therefore, have focused to identify the kinematic components associated with excessive peak knee abduction moments during cutting manoeuvres. A wider foot lateral placement (Dempsey et al., 2009; Fox 2018; Havens and Sigward, 2015c; Jones et al., 2016b), greater lateral trunk flexion away from the intended direction (Dempsey et al., 2009; Fox 2018; Jones et al., 2016b), hip internal rotation angles (Havens and Sigward, 2015d; McLean et al., 2005; Sigward and Powers, 2007), as well as high knee abduction (Jones et al., 2016b; Kristianlund et al., 2014; McLean et al., 2005) and hip flexion (Fox 2018; McLean et al., 2005) angles at initial contact have been described as some key factors related to the larger peak knee abduction moments.

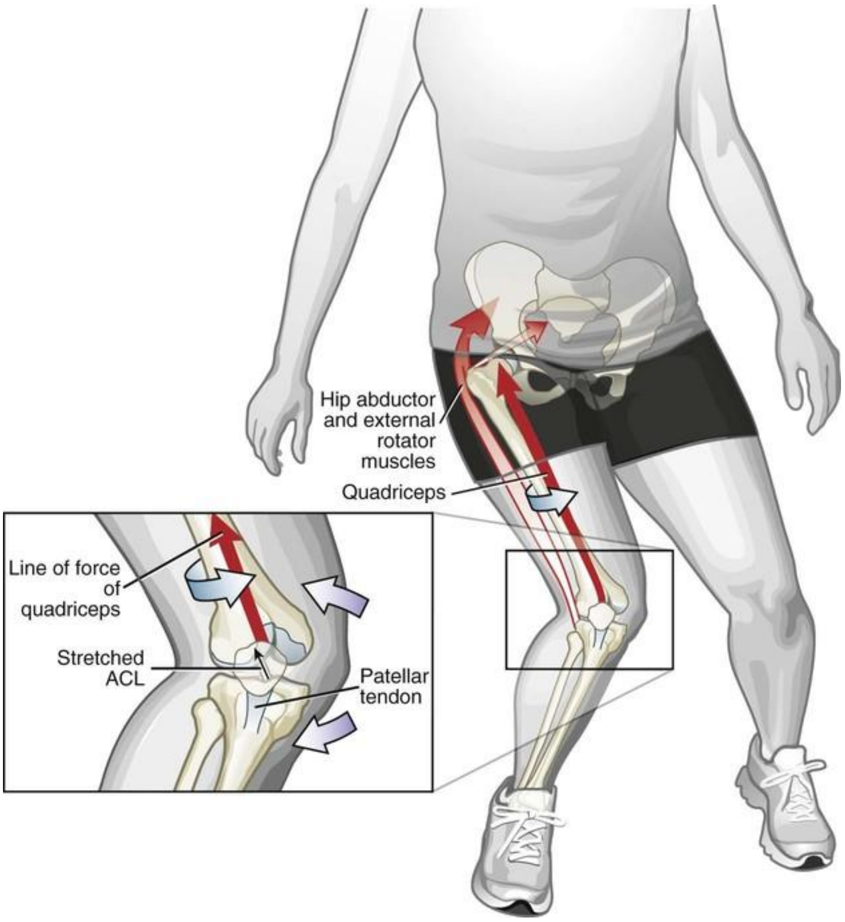

FIGURE 14. Neumann, D. A. 2010. ‘Dynamic valgus’ occurs when distal femur moves toward and distal tibia away from the midline of the body. Kinesiology of the musculoskeletal system: foundations for rehabilitation (Figure 13-21). St Louis, MO: Mosby. Elsevier. Retrieved from https://musculoskeletalkey.com/structure-and-function-of-the-ankle-and-foot/#f0040.

Furthermore, the joints in the lower extremities acts as a shock absorbers for the whole body and, therefore, sufficient joint flexion movements are critical to attenuate the ground reaction forces during athletic tasks (Fox et al., 2014). Decreased/insufficient knee flexion have found to be associated with ACL injuries (Hewett et al., 2006, Leppänen et al., 2017), particularly, because this kinematic inadequacy increases the load of the passive joint restrains, such as knee ligaments (Schmitz et al., 2002). Additionally, internal rotation of the tibia, particularly, in combination with extended knee (< 30° of knee flexion) is considered as an important loading mechanism of the ACL (Markolf et al., 1995). Pivot landing test findings (Oh et al., 2012) and cadaver study results (Meyer & Haut 2008) supports this idea demonstrating that, especially, during tibial internal rotation the ACL strain values increases. Interestingly, while laboratory testing (Fleming et al., 2001) indicates that external rotation of the tibia doesn’t increase the

ACL strain values, the video-analysis findings (Krosshaug et al., 2007; Olsen et al., 2004) demonstrates that tibial rotation, both internal and external, is observed during authentic ACL injury situation – and therefore external rotation, as well, should be considered as a contributing factor to the injury.

Although, many questions need to be answered, as the previous studies are not in agreement of the role/importance of the different biomechanical factors, there seems to consensus and strong indication suggesting that, most likely, the injury is a result of a *movement combination across multiple planes*. Particularly, since the concurrent motions outside of normal range across multiple planes increases the stress in knee ligaments, compared to abnormal movements in a singular plane alone. (Brown et al., 2014; Fox et al., 2014.) Findings from Boden and colleagues (2000) suggests, that the common body position in which the injury occurs include the tibia in external rotation, the knee close to full extension, and a deceleration motion followed by a valgus collapse. In addition, Olsen et al., (2004) described, that the typical ACL injury mechanism in women handball players was a “forceful valgus collapse with the knee close to full extension combined with external or internal tibial rotation” (figure 15). It is still under speculations, however, which are the most harmful movements combinations (Hashemi et al., 2011), and in which order these combined movements occur (Fox et al., 2014; Olsen et al., 2004).

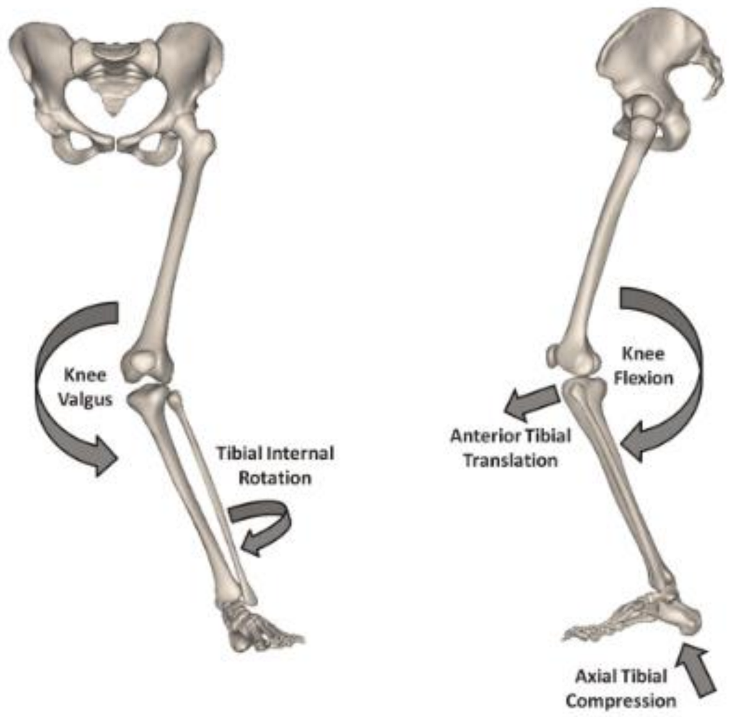

FIGURE 15. Levine, J. W., et al. 2013. A combination of anterior tibial shear force, and knee abduction and internal tibial rotation moments. In Clinically relevant injury patterns after an anterior cruciate ligament injury provide insight into injury mechanisms. The American journal of sports medicine 41 (2), 385-395.

The current evidence indicates that the ACL injury occurs approximately 30 to 100 milliseconds after initial ground contact (Hewett et al., 2012; Koga et., 2010; Koga et al., 2011); most likely within the first 40ms after IC (Koga et al., 2018). The precise mechanism resulting to ACL injury is a multistage process. For instance, when an athlete decelerates during the change of direction a posterior, medially directed and vertical ground reaction forces are generated (Weinhandl & O'Connor 2017). The increased peak posterior ground reaction forces during athletic tasks, particularly, increases a flexion moment in relation to the knee. The following sequence involves the quadriceps muscles to contract eccentrically to control/balance the knee flexion moment. (Yu & Garrett 2007.) The critical phase then develops as the contraction of the quadriceps muscles generates an anterior tibial shear force on the proximal end of the tibia through the patella tendon, while hamstring muscles attempts to restrain the anterior translation of the tibia (Yu & Garrett 2007.) This *anterior tibial shear force* is widely recognised as a significant ACL injury risk factor (Hashemi et al., 2011). Increased vertical ground-reaction forces during jump-landings have been associated with ACL injuries (Hewett et al., 2005; Leppänen et al., 2017), however, it is under speculation whether larger ground reaction forces should be considered as risk factor for cutting related knee injuries (Kristianslund et al., 2014).

3.2.5 Risk Factors Associated with Knee Injuries

By the same token, as in respect of the ankle injuries, researchers have been very ambitious in their attempts to identify both external and internal risk factors for knee injuries. Hägglund and Waldén (2015) describes that based on several studies there is a wide agreement on three major intrinsic risk factors associated with acute knee injuries (particularly ACL injuries): female sex, age and previous injury. These risk factors have been widely identified as essential risk factors in many team sports (Boden et al., 2010; Smith et al., 2012a).

For instance, female athletes tend to suffer knee injuries, particularly severe injuries treated with surgery, more often than males (Swenson et al., 2013). According to previous findings (Agel et al., 2005; Bahr & Krosshaug 2005; Krosshaug et al., 2006; Walden et al., 2011) the ACL injury incidence is 2- to 6-fold greater in young female athletes compared to males who compete in pivoting and landing sports. Moreover, several studies indicate that there is a clear relation between previous lower extremity injury and increased susceptibly of suffering knee injuries (Boden et al., 2010; Fulton et al., 2014; Hewett et al., 2006; Hägglund & Waldén 2016; Smith et al., 2012a). For instance, it has shown that previous ACL injury multiplies the knee injury in rate in both female (Hägglund & Walden 2016) and male soccer players (Waldén et al., 2006). The rate of subsequent ACL injury to either the contralateral or reconstructed knee is found to be 30% among Australian football players, while the rate was especially high among young players (<21 years) (Lai et al., 2018).

Additionally, the relationship between age and knee injury rates is well documented, however, the findings should be interpreted in a detailed manner between the males and females. Studies have demonstrated that: **1)** the ratio of all knee injuries increases among athletes with age (in both sexes), as the children grow up to become adolescents (Shea et al., 2004), **2)** ACL injury risk is high in girls during their adolescence (Hägglund & Waldén 2016; Shea et al., 2004, Waldén et al., 2011), however, the risk tends to decrease as female athletes mature (i.e. move from high school to college), as well as when the level of play increases, **3)** among males the incidence of ACL injuries increases consistently with age, as they move from high school to college and, furthermore, to professional level, **4)** higher overuse injury rates are seen among college athletes compared to high school athletes (Roos et al., 2015).

Furthermore, insufficient neuromuscular control of the body has been identified as the primary risk factor for ACL injuries (Benjaminse et al., 2010; Fox et al., 2014) and this area of study, therefore, has aroused a plenty of clinical interest. While some studies (Pollard et al., 2003) haven't been able to detect any essential differences in biomechanical variables between males and females during cutting and landing tasks, there seems to be a wide agreement in the literature, indicating that female sex is related to abnormal biomechanics during athletic movements (Brown et al., 2014). For instance, some studies have demonstrated that during athletic tasks females tend to display decreased knee flexion angles (Beutler et al., 2009; Malinzak et al., 2001) and decreased peak knee flexion moments (Sigward & Powers 2006) compared to males. Furthermore, during sidestepping young female soccer players demonstrated greater external knee valgus moments (Sigward & Powers 2006; Sigward et al., 2012), as well as decreased peak flexion and larger knee valgus angles compared to males (Malinzak et al., 2001).

4 PREVENTION OF LOWER EXTREMITY INJURIES – THE ROLE OF FOOT LANDING TECHNIQUE

Over 25 years ago van Mechelen and colleagues (1992) described the injury prevention research as a four-step sequence. **1)** The first step includes that the magnitude of the problem must be identified and present in terms of the incidence and severity of injuries. **2)** Secondly, the risk factors and injury mechanisms associated with injuries should be recognized. **3)** The following step involves introducing measures that could, potentially, reduce the risk for future injuries. These measures should be based on the knowledge of aetiological factors and the injury mechanisms identified during the second phase. **4)** Finally, the effectiveness of these preventive measures should be evaluated by repeating the first step. This should be accomplished by implementing, preferably, randomized clinical trials.

Running Literature. In recent years, one of the most notable trends in sports injury prevention research has been neuromuscular training programs (Webster & Hewett 2018). Several intervention studies have shown that by means of these programs the players physical ability can be develop, while the injury incidence decreases significantly (Lauersen et al., 2014; Webster & Hewett 2018). Another interesting topic with respect to sport injuries, and in terms of provoking a discussion, stems from the running literature. Previous studies have attempted to figure out, whether the foot-strike pattern can predict lower extremity injuries (Altman & Davis 2016; Daoud et al., 2012). Thus far, the consensus hasn't reached. Some biomechanical studies have demonstrated that forefoot strike-pattern results in a smaller collision forces (Almeida et al., 2015; Lieberman et al., 2010) and decreased knee valgus moments (Kulmala et al., 2013) compared to rearfoot strike pattern. Furthermore, Daoud and colleagues (2012) reported less repetitive stress injuries among forefoot strikers, however, the traumatic injury rates didn't differentiate between these running styles. Additionally, findings from a prospective study (Altman & Davis 2016) demonstrated that habitual barefoot runners (running style which is mainly associated with forefoot/midfoot striking) suffered the same amount of injuries than shod runners (running style mainly associated with rearfoot striking). It is worth noting, however, that in this study the findings demonstrated a different injury location between the running groups: barefoot runners suffered higher amount of calf injuries and injuries to the plantar surface of the foot, whereas shod runners suffered more knee and hip related injuries.

Foot Position & Whole-Body Biomechanics. Not only in respect of running injuries, it has also been suggested that suboptimal foot positioning during initial contact could be an aetiology of acute lower extremity injuries (Fong et al., 2009a; Boden et al., 2009; van der Does et al., 2015). For instance, ankle sprains may occur since the foot landing pattern effects the biomechanics, mainly via changes of the moment arm along the subtalar joint, of the lower extremities (Fong et al., 2009a). Furthermore, landing or changing direction with decreased plantarflexion during athletic tasks may be a risk factor for knee injuries, potentially by lessening the ankle joint's capacity to absorb the impacts from the ground, while forcing the knee to attenuate increased loads (Weiss & Whatman 2016). The effects of foot landing pattern/technique to body biomechanics have been studied mainly during athletic tasks, such as jump landings (Beutler et al., 2009; Cortes et al., 2007; Tran et al., 2016; Valenzuela et al., 2016; van der Does et al., 2016) and cutting manoeuvres (Boden et al., 2009; Cortes et al., 2012; David et al., 2017; Donnelly et al., 2017; Yoshida et al., 2016).

'Toe-Landings' During Cutting. The findings from Kristianslund and colleagues (2014) demonstrated that in female handball players the 'toe landings' during cutting task resulted in a substantially decreased external knee abduction moment, as well as a decreased valgus angle. In fact, the results demonstrated that the feet pointing 16° more downward correspondent to a 13% decrease in knee abduction moment. The authors hypothesized that 'toe-landings' may help to lower the risk for ACL injuries via decreasing the external knee abduction moment. In line with these results, Yoshida and colleagues (2016), as well, reported smaller knee valgus angles with those female handball athletes who used forefoot landings, instead of rearfoot technique, during cutting tasks. Moreover, Donnelly and colleagues (2017) investigated female field hockey players and demonstrated that, during unplanned sidestepping, there were distinct differences in kinetics between athletes who utilized forefoot landing pattern compared to those who used rearfoot landing technique (Figure 16). Rearfoot strikers absorbed more power through their knee joint, while presenting increased knee abduction and non-sagittal plane ankle moments. Forefoot strikers, conversely, absorbed more power at the ankle joint, while demonstrating decreased knee abduction and non-sagittal plane ankle moments. The authors suggested that rearfoot strikers may have elevated risk for knee injuries while, in contrast, the forefoot strikers may possess higher risk for ankle related injuries.

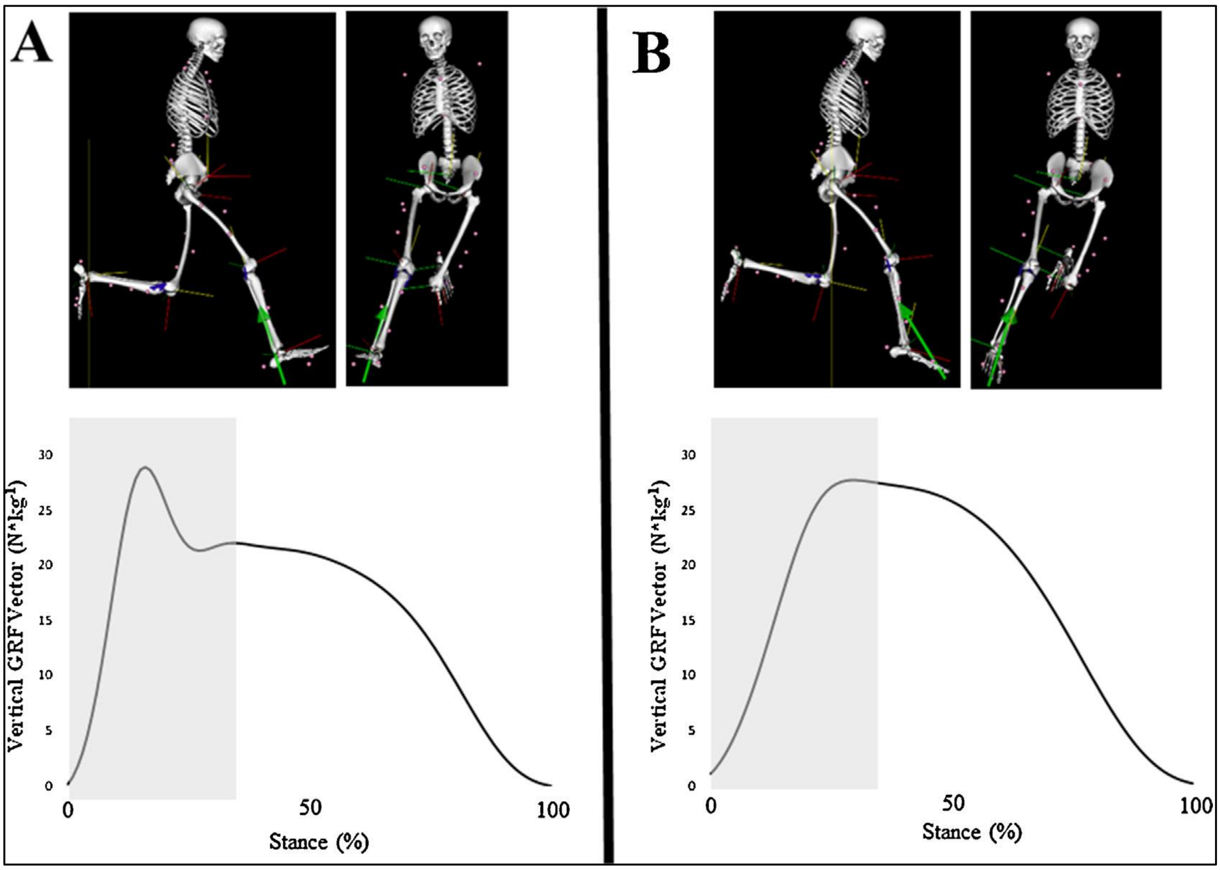

FIGURE 16. Donnelly, C. J., et al. 2017. Frontal and sagittal view of rearfoot (A) and forefoot (B) landing patterns at initial contact. The weight acceptance phases (first 30% of stance) are shaded in grey for the corresponding rearfoot (A) and forefoot (B) landing patterns. In Joint dynamics of rear-and fore-foot unplanned sidestepping. Journal of science and medicine in sport, 20 (1), 32-37.

Different Cutting Angles. Cortes and colleagues (2011) observed different kinematics between two landing techniques among female soccer players whom performed 45° sidestep cutting and 180° pivoting procedures. Rearfoot landing pattern resulted in greater knee valgus angle and decreased knee flexion angle during the sidestep cutting task compared to forefoot landing. In contrast, during the pivot task, increased knee valgus angle was observed in combination with the forefoot strike. Moreover, during both cutting tasks the participants who used the rearfoot landing presented decreased knee flexion angles compared to the forefoot group. Based on these findings the authors underlined that the injury mechanism for knee injuries could be dependant of the combination including both: the landing pattern utilized, as well as the characteristics of the cutting manoeuvre performed. Additionally, the authors suggested that the rearfoot technique could be potentially more harmful with respect to ACL injuries, since this technique, during sidestep manoeuvres, leads to a “risky” combination of increased external knee abduction moment and decreased knee flexion. (Cortes et al., 2012)

Transverse Plane Foot Motions. Some studies have also evaluated the transverse plane foot kinematics during athletic tasks. Tran and colleagues (2016) demonstrated that ‘toe-in’ (internal rotation of the foot or foot adduction) landings, relative to ‘neutral position’, increased many of the factors associated with ACL injuries: knee internal rotation angles and moments, peak knee valgus angle and hip adduction angle. Additionally, ‘toe-in’ position decreased knee flexion angles and increased tibial internal rotation. In contrast, ‘toe-out’ landings seemed to align the lower limb better, with less hip adduction, knee abduction and knee internal rotation. Sigward and Powers (2007), moreover, presented similar results with respect to the kinematics during sidestep cutting. They found that larger internally rotated foot angle at initial contact was associated with excessive external knee abduction moment.

Video-Analysis. To consolidate some of the hypothesizes based on these biomechanical studies, Boden and colleagues (2009) performed a video-analysis study to figure out abnormalities in hip and ankle kinematics which may predispose ACL injuries. In this study, they analysed the injury mechanisms of actual playing situations in different sports that led to ACL injury, and compared the kinematic findings to a similar situation where an athlete didn’t suffer an injury. In respect of the landing technique during athletic tasks, the main difference was that the players who suffered an injury landed with flatfoot or rearfoot and reached the flatfoot position sooner, whereas the non-injured players presented significantly more plantarflexion and landed with forefoot. Another, very recent, video analysis study of actual noncontact ACL injuries (Koga et al., 2018) demonstrated new findings that should be interpreted carefully. This study was enabled to describe the kinematics of the ankle during the injury sequence. During cutting related ACL injuries all the players landed with a heel strike, while both dorsi- and plantarflexion was observed at IC. Furthermore, the foot was inverted and externally rotated at IC in most of the players. Interestingly, the ankle inversion and internal rotation rapidly increased (in most of the players) after IC. An excessive inversion in combination with mild internal rotation, therefore, was identified 40ms after IC (i.e., presumably at the time of injury). One of the figure illustrations of actual injury sequence, furthermore, demonstrated that a clear ‘dynamic valgus’ occurred during the first 40ms. This observation with respect to the ankle kinematics argues, clearly, against the previous hypothesis (Hewett 2005), suggesting that ankle eversion/pronation is present during ‘valgus collapse’.

5 PURPOSE & HYPOTHESES OF THE STUDY

The purpose of this study is to investigate the association of the foot landing pattern during cutting manoeuvres to the incidence of acute noncontact knee and ankle ligament injuries in young team-sport athletes. Previous biomechanical studies have investigated the foot kinematics in relation to the known biomechanical risk factors for lower limb injuries, however, to my knowledge, there is no previous prospective studies that have reported the association between foot landing pattern and injuries in team-sports. The need for prospective sport injury studies is well recognized, since the results of these studies, not only offer possible *new* explanations for injuries, but could also give support to the hypotheses framed from the findings of previous biomechanical studies. The aim of this study is to provide new evidence for the professionals working with athletes to help to develop even more successful injury reduction/prevention programs.

The research questions are as follows:

1.) Is there an association between the foot landing technique (analyzed as a sagittal plane foot-alignment relative to the ground at initial contact) to the incidence of ankle and knee injuries?
2.) Is there an association between the foot landing kinematics (analyzed as frontal, sagittal and transverse plane ankle kinematics at initial contact) to the incidence of ankle and knee injuries?
3.) Is there different foot landing kinematics and/or landing techniques associated with ankle injuries compared to knee injuries?

The approach of this study was designed, on purpose, to be ‘pragmatic’ and focus only on kinematics. The reason for this was that, since the professionals working with the athletes mainly utilizes quality analysis of human movement (e.g., visual observation), it was truly desired to provide clinically relevant, easily observable and many ways applicable data for these purposes. In other words, to figure out, if there is any indication whether some athletes should be suggested to alter their foot landing pattern during cutting manoeuvres to reduce the risk for injuries. The need for this type of approach is presented in the previous literature, suggesting that *a screening test* to identify athletes with poor cutting and pivoting mechanics is warranted due to the specific nature of certain sport injuries (Jones et al., 2014).

I hypothesize that players at greatest risk for both ankle and knee injuries are those who demonstrate: 1) heel-strike angles above average, and 2) larger ankle internal rotation angles. Furthermore, I hypothesize that heel-strikers, considered as a one group, presents higher rates of injuries than forefoot strikers.

6 MATERIALS & METHODS

6.1 Study Design & Participants

This study is part of the large prospective PROFITS-study (Predictors of Lower Extremity Injuries in Team Sports) conducted in Tampere Research Center of Sports Medicine, UKK Institute, Finland between 2011 and 2015. It was carried out in accordance with the Declaration of Helsinki and approved by the Ethics Committee of the Pirkanmaa Hospital District (ETL-code R10169). For more information, the protocol of the study has been described elsewhere (Pasanen et al., 2015).

Participants were recruited from 6 basketball and 6 floorball sport clubs of the Tampere region in Finland – including a total of 9 basketball and 9 floorball teams that agreed to participate. In each study year (2011, 2012, and 2013), players from the 2 highest junior league levels were invited to participate. Junior aged players (21 and under) and official members of the participating teams were eligible to participate – both males and females. Players free of current lower extremity injuries took part in the baseline measurements. Players with previous lower limb injuries were eligible to participate if they were fully recovered from their previous injury. Therefore, 9 players did not perform the cutting tests due to ongoing injury or illness. All subjects were ordered to provide written informed consent. Additionally, players younger than 18 years were required to provide a parental consent.

A total of 396 athletes participated in the cutting technique tests. Test results from a total of 15 athletes were completely excluded from the analysis due to lack of valid trials. Of these, 5 players were excluded since they couldn’t technically perform the tests in a desired way, while 10 subjects were excluded due to random errors encountered while processing the 3D-data (e.g., incomplete force registration of the force plates, gaps in marker trajectories that could not be interpolated). For these same reasons, it was, however, possible to record valid trials partially from some players (e.g., only another leg or another task). Therefore, every player who had adequate amount (3) of valid trials in any of the tests, and whichever leg, were observed prospectively for one year for ankle and knee injuries. 26 athletes were lost to follow up.

Complete data for the baseline cutting tests and prospective registration of injury through 1-year, as well as match/training exposure were obtained from a total of 355 players: 183 basketball and 172 floorball players, 185 males and 170 females.

6.2 Baseline Measurements & Test Protocol

At baseline, each participants height, weight, knee widths, ankle widths and leg lengths were measured, and body mass index (BMI, kg/m^2) calculated. In addition, players filled out a questionnaire regarding information such as demographics, playing experience and the time-loss injuries they had sustained during the past 12 months. Series of physical screening procedures were conducted in 3D-motion analysis laboratory at each year players enrolled the study. These tests included two different types of cutting technique tasks: 90° and 180° cutting tests. Basketball players performed only the 180°cutting technique test, while floorball players carried out both the 90° and 180° tests, respectively. In a study protocol description (Pasanen et al., 2015), both these test procedures were presented as *new tests*, suggesting that no previous study had implemented these tests in this same detailed manner.

The players wore a tight shorts and indoor sport shoes during the test. Male players were shirtless, whereas female players used sport bras. Prior to the cutting procedures, the subjects had performed a standardized warm-up procedure. During the 90° test, the players were instructed to approach the two separate force-plates along an imaginary diagonal line passing the plates (i.e., enter the square-shaped force-plate through one of the two top corners), plant the other foot onto the force-plate which they entered, change direction away from their foot, and finally, run through the bottom corner of the force-plate which they initially entered (Figure 17). During the 180° cutting task the players were instructed to perform a straight run toward the force-plates, enter the force-plates from the middle of either left or right-side, plant only one foot onto the further plate, and after performing a 180° rapid turn sprint straight back to the starting position (Figure 17). The cutting procedures were desired to be performed in game-like situations. The floorball players, therefore, executed all the cuttings while handling the floorball stick. Additionally, during 180° cuts, they passed the ball to an assistant player before sprinting onto the force-plates. In similar manner, basketball players passed the basketball to another player, then sprinted onto the force-plates and performed the pivot turn, and finally received a pass at the same spot where they initiated the trial. The approach speeds weren't monitored; however, players were instructed to perform the procedures in the same manner as in real-game situations. A minimum of 3 successful trials were collected from each participant. A trial was considered valid if the player completed the cut as described above.

*It should be noted, that a very small number of players (during the first year of testing) were incorrectly instructed to perform the 180° cuts in a way that they planted their foot onto the nearest force-plate. These trials, however, weren't considered particularly divergent compared to the trials where the foot was planted onto the furthest force-plate and were, therefore, accepted to the analysis.

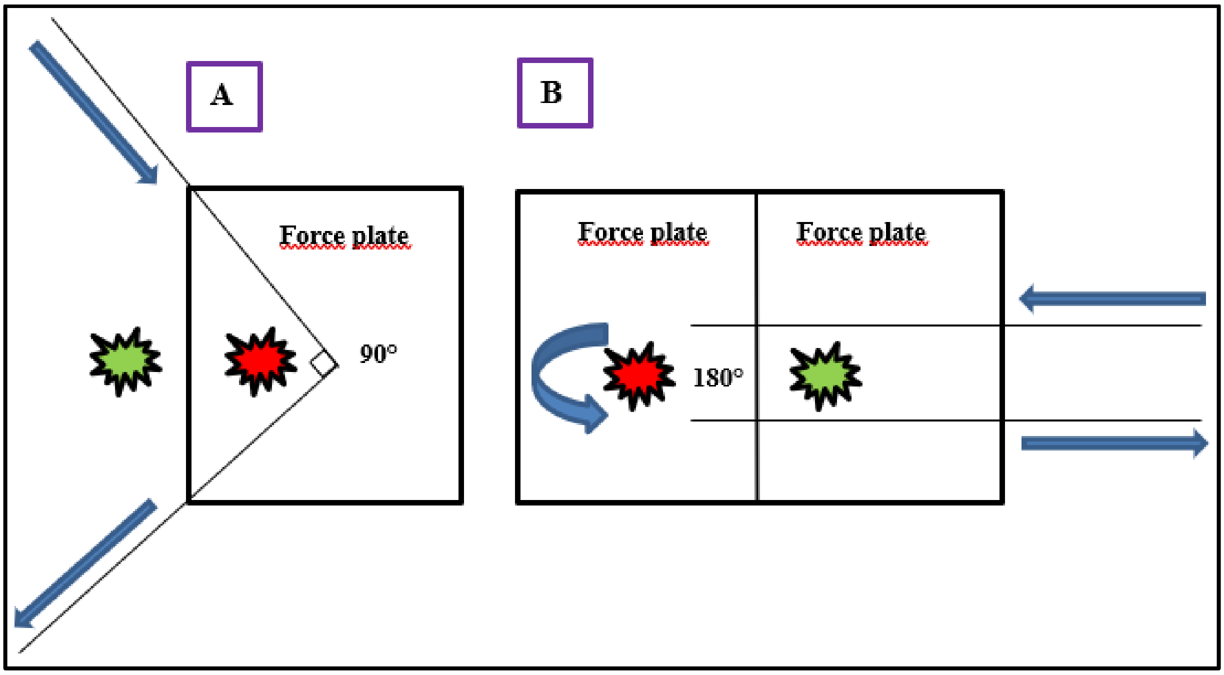

FIGURE 17. Experimental setup for 90° left-leg cut (A) & 180° right-leg cut (B). The blue arrow indicates the original direction of progression. The red star indicates the position of the 'performing foot', while the green star illustrates the foot position of the 'support leg'.

6.3 Instrumentation & Motion Data Collection

Placement of reflective markers were performed according to a full body Plugin gait model (Vicon Nexus v1.7; Oxford Metrics, Oxford, UK). This included 16 reflective markers that were placed over anatomical landmarks on the lower extremities (Figure 18): on the shoe over the second metatarsal head, over the posterior calcaneus, lateral malleolus, lateral shank, lateral knee, lateral thigh, anterior superior iliac spine, posterior superior iliac spine. Two physical therapists were responsible for placing markers uniformly. 8 high-speed cameras (Vicon T40, Vicon Motion System) and 2 force platforms (AMTI BP6001200; AMTI, Watertown, MA) were used to record marker positions and ground reaction force data synchronously at 300 and 1500Hz, respectively. A static calibration trial was completed prior to task to determine the anatomical segment coordinate systems. Marker trajectories were identified with the Vicon Nexus software (Vicon Nexus v1.7; Oxford Metrics). Interpolation using the Pattern Fill algorithm was performed if the markers disappeared momentarily (time period of 25 frames or less). We excluded trials if the reflective markers were out of sight for longer than 25 frames. Both movement and ground reaction force were filtered using a fourthorder Butterworth filter with cutoff frequencies of 15Hz [14]. Data analyses were performed using the Plug-in Gait model (Vicon Nexus v1.7, Oxford Metrics).

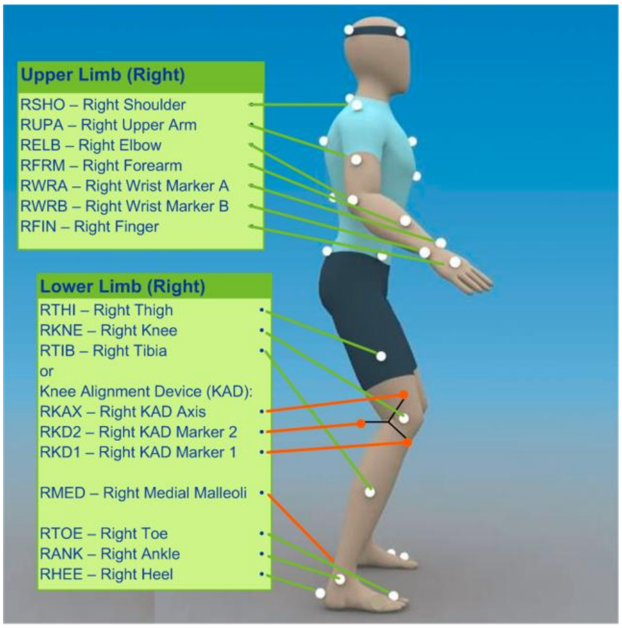

FIGURE 18. Placement of the markers according to Plug-In gait model (Vicon, Oxford, UK).

The foot initial contact phase (IC) was defined as the period when the unfiltered normalized ground-reaction force exceeded 20 N. In the current study, selected multiplane variables during the IC of the cutting procedures were analyzed. These variables included relative ankle angles in all diagonal planes at initial contact (dorsi-/plantarflexion, inversion/eversion, internal/external rotation), as well as absolute angles of the foot strike pattern (heel strike, midfoot strike, forefoot strike) at IC. The ankle angles were defined as relative angles between the shank and the foot. Dorsi- and plantarflexion was defined as the angle between the foot vector (projected into the foot sagittal plane) and the sagittal axis of the shank (Figure 19). Foot internal and external rotations were measured about an axis perpendicular to the foot vector and the ankle flexion axis. These angles are the angles between the foot vector and the sagittal axis of the shank, projected into the foot transverse plane (Figure 19). Inversion and eversion are measured as the rotations about the long axis of the foot, projected into the foot frontal plane. Foot strike pattern was defined as the angle between the long axis of the foot and its projection onto the laboratory floor. Angle angles and foot strike pattern were determined across 3 successful trials. Both legs, if enough valid trials, were analyzed and the mean angles for each leg was calculated and used in the analyses.

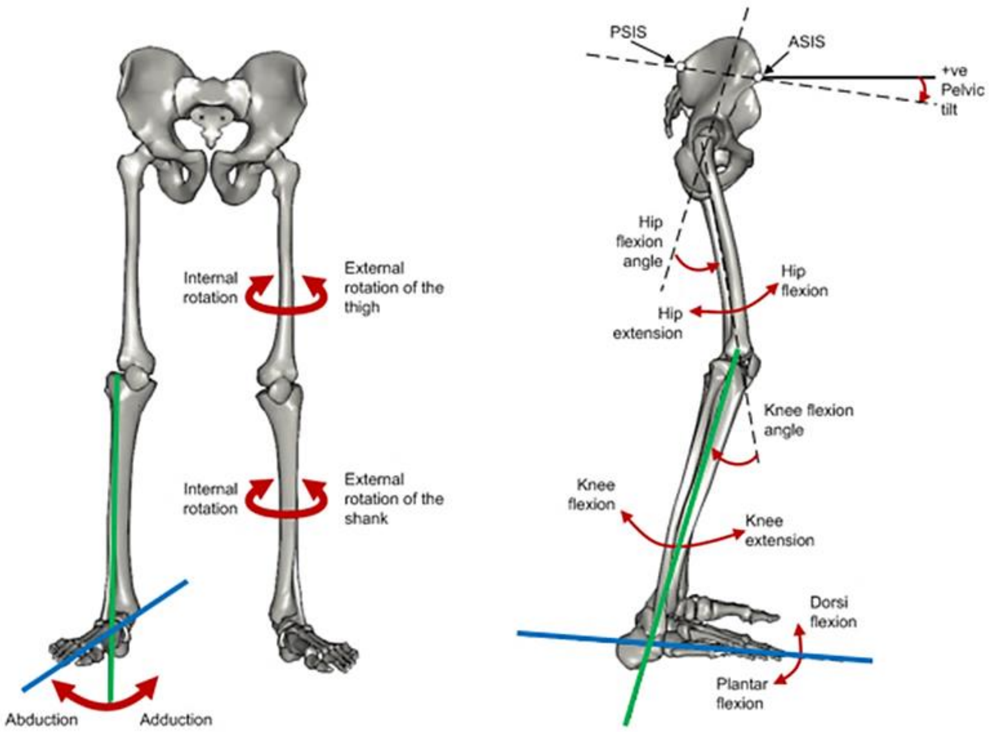

FIGURE 19. Kinematic variables according to lower limb Plug-In gait model (Vicon, Oxford, UK). Green line indicates the sagittal axis of the shank, blue line represents the foot vector.

6.4 Injury and Exposure Registration

'Injury' was defined as any acute knee or ankle injury that resulted in an athlete being unable to fully participate in training or match play for at least 24hours. During the prospective follow-up, team coaches' recorder the injuries, while 5 study physicians were responsible for collecting the injury data on a weekly basis. The teams were contacted once a week to check for possible new injuries and gather the information about the injury time, place, cause, type, location and the time-loss due to the injury. Each injured player was contacted via telephone and interviewed by a study physician using a structured questionnaire. In the current analysis, all noncontact knee and ankle ligament injuries that occurred during a match or scheduled team training were included. The coaches were responsible for collecting the data concerning the player participation in team training and matches using a team diary. Player attendance in a training session (yes/no), duration of a training session (h), and attendance in each period of a game (yes/no) were recorded for each player and this data was emailed once a month.

6.5 Statistical Methods

The players who suffered a lower limb ligament injury during the follow-up were compared to the uninjured athletes. An independent-samples t test was performed for the normally distributed variables (height, weight), while the Mann-Whitney U test was used to test the variables that were not normally distributed (age, BMI, exposure variables). The injury incidence was calculated as the number of injuries per 1000 player-hours, while reported with 95% CIs.

When investigating the complex association of risk factors for sport injuries a multivariate statistical approach is suggested to be used (Bahr & Holme 2003). The strength of survival analysis (also known as *time-to-event analysis*), such as Cox Regression model, is that it takes to account the individual characteristics (e.g., match or training participation) that may affect to the rate of injury occurrence. Additionally, this method takes into account the censorship, such as shorter lengths of follow-up resulted from several other reasons (e.g., illness, quitting the sport, turning professional) than due to the occurrence of an injury. (Bahr & Holme 2003).

Recently published papers (Nielsen et al., 2019a; Nielsen et al., 2019b) have also declared *time-to-event-analysis* as superior to other analytical concepts with respect to the prospective sport injury studies, mainly, since these enables the consideration of time-varying exposure variables, such as training loads and subsequent injuries.

In the present study, a total of 16 separate Cox mixed-effects models were created. A noncontact ankle or knee ligament injury during the follow-up was used as the outcome, while the leg was used as a unit of analysis. Each model included a single kinematic variable (the mean of 3 cutting trials) and a similar set of predefined covariates that might influence the risk of injuries: age, height, weight, sport, dominant leg, playing at adult level, and previous lower limb injury (injury of the ipsilateral or contralateral leg). The monthly exposure time from the start of follow-up until the injury or the end of follow-up was included in the models. The dominant leg was defined as the preferred leg when kicking a ball. Stepwise regression with backward selection was used in every model to remove the least useful predictors. One-at-a-time, a covariate with a p-value <0.10 was removed from the model starting with the highest value.

Cox hazard ratios (HRs) with 95% CIs were calculated. For improved interpretation, HRs were adjusted for a 5- unit change. Variables that had a P value <0.05 were considered significant. Statistical analyses were conducted in SPSS for Windows (v20.0.0; SPSS). The combined sensitivity and specificity of significant test variables were assessed by using a receiver operating characteristic (ROC) curve analysis. The test outcome was defined as excellent (0.90-1.00), good (0.80-0.89), fair (0.70- 0.79), poor (0.60-0.69), and fail (0.50-0.59).

7 RESULTS

7.1 Baseline and Injury Characteristics

Baseline Data. Complete data were obtained from 355 athletes: 183 basketball and 172 floorball players. This comprised a total of 694 legs (349 left and 345 right), since it was possible to analyze only the other leg from 16 athletes. The basketball players were significantly younger than the floorball players, whereas the floorball players had significantly more playing years, higher amount of total training hours and higher BMI compared with the basketball players (Table 3). In addition, girls were significantly younger than boys (p<0.01) and had significantly fewer playing years (p<0.001), as well as training hours (p<0.001) during the follow-up compared with the boys.

TABLE 3. Baseline Characteristics of Participants. [a]

	Basketball n=183		Floorball n=172		
	Girls (n=94)	Boys (n=89)	Girls (n=76)	Boys (n=96)	P-value [b]
Age, y	14.8±1.6	15.4±1.6	16.9±1.9	16.9±1.3	<0.001*
Height, cm	168.8±6.6	179.9±8.8	167.0±5.6	178.1±6.5	0.150
Weight, kg	60.9±8.9	69.6±12.8	61.7±7.5	69.2±8.0	0.337
BMI	21.3±2.6	21.4±3.0	22.1±2.5	21.8±2.2	<0.002*
Playing years	6.6±2.5	7.6±3.2	6.5±2.5	8.7±2.8	<0.003*
Training hours [c]	174.0±76.5	251.4±116.0	216.6±104.7	264.0±128.2	<0.001*

[a] Data are presented as mean (SD). [b] P-values presents the group comparison between all basketball & all floorball players. P-values are based on t-test for normally distributed & Mann-Whitney U test for nonnormally distributed variables. [c] Team practice hours/season.

Injury Incidence. During the follow-up a total of 38 noncontact ankle ligament injuries and 16 noncontact knee injuries were registered and included in the present analysis (Table 4). This comprised a total of 36 lateral ankle sprains, 1 syndesmotic ankle sprain, 1 medial ligament ankle sprain, 8 ACL ruptures, 5 unspecified knee ligament sprains, 2 MCL ruptures and 1 meniscus injury. Overall, floorball players suffered more ankle injuries, whereas basketball players sustained more knee injuries. Furthermore, more than twice as many injuries occurred to the dominant leg. In respect of ACL injuries, basketball athletes suffered a total of 3 and floorball players a total of 5 ACL tears. The overall noncontact ankle injury incidence was 0.24 injuries (95% CI, 0.16–0.32) and the overall knee injury incidence 0.10 (95% CI, 0.05–0.15) injuries per 1000 player-hours. In addition, the overall lower extremity injury incidence for girls was 0.56 (95% CI, 0.38–0.74) and for boys 0.19 (95% CI, 0.10–0.28) per 1000 player-hours. Table 4 provides a sport specific decomposition of the injury rates.

TABLE 4. Incidence of Lower Extremity Injuries in Training and Matches.[a]

	Floorball		**Basketball**		
Variable	Ankle (n=24)	Knee (n=7)	Ankle (n=14)	Knee (n=9)	Total
Boys	n=11	–	n=6	n=1	18
Girls	n=13	n=7	n=8	n=8	36
Left/Right[a]	10/14	4/3	7/7	4/5	25/29
Dom./non-dom[b]	12/8	4/2	11/2	6/2	33/14
Injury Incidence[c]	0.29 (0.17–0.40)	0.08 (0.02–0.15)	0.19 (0.09–0.29)	0.12 (0.04–0.20)	0.34 (0.25–0.43)

[a]Left leg/Right leg; [b]Dominant leg/Non-dominant leg; [c]No./1000 hours of exposure (95% CI);

During the follow-up three athletes suffered a ligament injury on both lower limbs: one of those athletes suffered a knee injury on both limbs, one suffered bilateral ankle sprains and one suffered a knee injury to one leg, while also suffering an ankle sprain to another limb. With respect to the ankle injuries, as many as 16 were recorded as new injuries, whereas in 22 cases there was a previous ipsilateral injury diagnosed. Moreover, in respect of the knee injuries only in 6 cases there was a previous ipsilateral (n=4) or contralateral (n=2) injury diagnosed.

7.2 Foot-landing Biomechanics and the Risk of Lower Extremity Injuries

Unadjusted group comparison between the injured and uninjured players unveiled no significant differences in respect of the variables investigated: neither in 90° (Tables 5 & 6) or 180° (Tables 7 & 8) cutting tasks.

TABLE 5. Foot Landing Kinematics from 90° Cuts & Ankle Injuries.[a]

	Uninjured Ankles (n=316)	Injured Ankles (n=23)	
Variable	Angles, degree at IC	Angles, degree at IC	p-value
Dorsi (+)/Plantarflexion	-1.13±11.1	-3.20±11.2	0.386
Inversion (+)/Eversion	3.07±3.3	2.54±4.2	0.189
Int. (+)/Ext. Rotation	-16.69±15.6	-12.43±17.9	0.182
Forefoot (+)/Heel strike	-7.61±13.7	-5.02±11.1	0.503

[a]Data are presented as mean (SD); IC=initial contact; positive values refer to ankle dorsiflexion, inversion, internal rotation and forefoot strike pattern (i.e., heel higher than toes).

TABLE 6. Foot Landing Kinematics from 90° Cuts & Knee Injuries.[a]

	Uninjured Knees (n=332)	Injured Knees (n=7)	
Variable	Angles, degree at IC	Angles, degree at IC	p-value
Dorsi (+)/Plantarflexion	-1.23±11.1	-3.26±9.6	0.631
Inversion (+)/Eversion	3.05±3.41	2.18±3.41	0.654
Int. (+)/Ext. Rotation	-16.47±15.6	-12.94±21.8	0.941
Forefoot (+)/Heel strike	-7.48±13.55	-5.46±12.6	0.738

[a]Data are presented as mean (SD); IC=initial contact; positive values refer to ankle dorsiflexion, inversion, internal rotation and forefoot strike pattern (i.e., heel higher than toes).

TABLE 7. Foot Landing Kinematics from 180° Cuts & Ankle Injuries.[a]

	Uninjured Ankles (n=618)	Injured Ankles (n=37)	
Variable	Angles, degree at IC	Angles, degree at IC	p-value
Dorsi (+)/Plantarflexion	-9.39±10.0	-10.64±8.5	0.807
Inversion (+)/Eversion	2.12±3.65	1.71±3.35	0.598
Int. (+)/Ext. Rotation	-12.04±17.7	-8.72±17.8	0.336
Forefoot (+)/Heel strike	9.87±10.7	11.18±8.5	0.745

[a]Data are presented as mean (SD); IC=initial contact; positive values refer to ankle dorsiflexion, inversion, internal rotation and forefoot strike pattern (i.e., heel higher than toes).

TABLE 8. Foot Landing Kinematics from 180° Cuts & Knee Injuries.[a]

	Uninjured Knees (n=640)	Injured Knees (n=15)	
Variable	Angles, degree at IC	Angles, degree at IC	p-value
Dorsi (+)/Plantarflexion	-9.40±10.0	-12.27±7.6	0.326
Inversion (+)/Eversion	2.11±3.7	1.46±2.5	0.687
Int. (+)/Ext. Rotation	-11.9±17.7	-11.40±16.8	0.926
Forefoot (+)/Heel strike	-9.89±10.7	-12.50±6.6	0.414

[a]Data are presented as mean (SD); IC=initial contact; positive values refer to ankle dorsiflexion, inversion, internal rotation and forefoot strike pattern (i.e., heel higher than toes).

The results from Cox Regression analysis showed that only the transverse plane foot internal rotation, in both cut tasks, were significantly associated with a new ankle injury (Table 9). During the 90° cut, each 5° increase in foot internal rotation was associated with a 1.16 times higher risk for ankle injury (p=0.045, 95% CI, 1.00-1.35), whereas during the 180° cut each 5° increase in foot internal rotation was associated with a 1.14 times higher risk for ankle injury (p=0.01, 95% CI, 1.03-1.26). No significant association was observed in any other kinematic variable investigated. ROC curve analysis for both foot internal rotation at IC and eversion at IC showed an area under the curve of 0.6, indicating a poor combined sensitivity and specificity of the test.

TABLE 9. Association Between Foot Internal Rotation (90° cut) & Noncontact Ankle Injury Risk.[a]

Variable	Risk Factor[b]	p-value
Foot Internal Rotation	1.16 (1.00-1.35)	0.045*
Dominant leg	2.18 (0.9-5.3)	0.085
Age	0.821 (0.65-1.04)	0.099

[a]Data are presented as hazard ratio (95% CI). [b]Hazard ratio for 5-unit change.

TABLE 10. Association Between Foot Internal Rotation (180° cut) & Noncontact Ankle Injury Risk.[a]

Variable	Risk Factor[b]	p-value
Foot Internal Rotation	1.14 (1.03-1.26)	0.010*
Dominant leg	2.64 (1.28-5.5)	0.009*
Previous Ankle Injury	2.43 (0.95-6.2)	0.065
Sport	Floorball: 1.91 (0.89-4.1) Basketball: 1.00	0.097

[a]Data are presented as hazard ratio (95% CI). [b]Hazard ratio for 5-unit change.

8 DISCUSSION

Despite the fact, that large number of biomechanical studies have been conducted (Fox et al., 2014) and very motivated results gathered from various neuromuscular training programs (Webster & Hewett 2018), the occurrence of knee (Mall et al., 2014; Peterson & Renström 2016, 398) and ankle injuries (Doherty et al., 2014) is still very high in many sports. The prevention of these injuries, therefore, has become a growing cause for concern due to the significant repercussions and rehabilitation costs that follows these unwanted events (Bahr et al., 2005; Brown et al., 2014; Fox et al., 2014; Hunt et al.,2017; Imwalle et al., 2009). The purpose of this study was to investigate the association of the foot landing pattern during cutting manoeuvres to the incidence of acute noncontact knee and ankle ligament injuries in young team-sport athletes and, therefore, to provide further evidence of the biomechanical risk factors associated with lower limb injuries. The main results of this study demonstrated that, while there was some indication of foot internal rotation at initial contact on ankle injuries, no clear landing pattern, performed in a laboratory setting, could be described as particularly 'injurious' (i.e., strongly associated with lower extremity injuries). This main finding is thought-provoking, since it provides another piece to the puzzle to understand the role of 'individual movement characteristics' on injury occurrence.

8.1 Injury Incidence

In the present study, the overall injury incidence of noncontact ankle sprains was 0.24 injuries per 1000 player-hours. This incidence rate is 3-5 times smaller than reported in previous studies investigating the same sports (Pasanen et al., 2017; Pasanen et al., 2018), however, in the present study only players who suffered a *noncontact* injury was analysed, which likely explains this difference, since collision and body contact injuries are frequently observed, both in floorball and basketball (Pasanen et al., 2017; Pasanen et al., 2018). Furthermore, some of the athletes who suffered a noncontact ankle injury during the follow-up had to be dropped from the final analysis, due to lack of valid data. This could, therefore, underestimate the incidence rate of the noncontact injuries. Moreover, it should be noted, that as many as 37 ankle injuries (out of a total of 38) occurred to the players representing 3 teams (out of a total of 6) involved in this study. Therefore, a thoughtful deliberation should be always implemented whenever comparing the studies, since the selection of the teams might have a notable impact on the injury rates.

Furthermore, the overall noncontact knee injury incidence was 0.10 injuries per 1000 player-hours. There was no significant difference in injury rates between the sports, and this trend has also been observed previously (Pasanen et al., 2017; Pasanen et al., 2018). However, in a similar manner as in ankle injuries, almost all (13/16) knee injuries occurred to players representing the same 3 teams. Based on these findings, it's worth noticing, that the selection of the teams may have a significant impact both in over- and underestimating the lower extremity injuries.

8.2 Foot Landing Pattern as an Injury Risk

While some clinical assessment tools, such as 'The Landing Error Scoring System', has been demonstrated as a valid screening protocol to evaluate the athletes at risk for ACL injuries (Padua et al., 2009; Padua et al., 2015), there is still a lack of such clinical tools to evaluate the lower extremity kinematics during cutting manoeuvres (Jones et al., 2014). The practical challenge, particularly in respect of the ankle and foot kinematics, is how to adequately evaluate the lower extremity kinematics during cutting with visual observation. Especially, if the assumption is that there is a necessity to evaluate the *entire* foot landing sequence during a fast pace cutting. Some authors (Donnelly et al., 2017), to wit, have suggested that the kinematic sequence of the foot during the stance phase could be, to some extent, derive/evaluate based on the position of the foot when it contacts the ground (i.e., initial contact), or even from the precise foot position just prior to ground contact. In the present study, therefore, it was decided to analyse the initial contact joint angles to evaluate the potential risk factors for lower limb injuries.

8.3 Forefoot Strike vs. Heel Strike

The association between an athlete's foot strike technique and injury risk has gained a lot of research attention within the running literature in recent years (Stearne et al., 2014; Kulmala et al., 2013). Moreover, some authors have suggested (David et al., 2016; Donnelly et al., 2017; Kristianslund et al., 2014; Montgomery et al., 2018; Yoshida et al., 2016) that heel strike pattern during cutting manoeuvres could be harmful landing technique compared to forefoot strike. Some of the suggested mechanisms has been related to higher knee valgus angles (Kristianslund et al., 2014; Yoshida et al., 2016), as well as greater work and power absorbed through the knee (Donnelly et al., 2017) of rearfoot strikers, which leads to a greater knee abduction moment. However, no clear trend was observed in this study with respect to these hypotheses. During the 1-year follow-up 14 heel strikers and 9 forefoot strikers suffered an ankle injury, whereas 4 heel strikers and 3 forefoot strikers suffered a knee injury. It should be noted, that the results of this study could be considered as reasonably reliable, since there was enough distribution of heel strikers (n=213 legs) and forefoot strikers (n=126 legs) during the 90° cuts. Moreover, a closer data observation revealed, and supported the claim of reliability, that these landing patterns could represent, very closely, the athletes 'natural' strike pattern. This conclusion could be made, since the values (of the selected variables at IC) of three separate successful trials, which were utilized to derive the single *average* foot strike-value, represented, in most cases, very consistent/similar landing pattern.

It should be noted, however, that in some cases there was a relatively clear variation between the strike pattern of consecutive trials, and some players, in fact, demonstrated both the heel and forefoot strike pattern. The fact, that some individuals have, what could be described as 'inconsistent strike pattern', isn't particularly surprising finding, since the players always must adjust their performing step with respect to many continuously changing variables, such as the approaching speed, the size of the selected stepping area, the position and posture of the penultimate step etc. However, the general question that arouses due to this phenomenon, and what shouldn't be brushed aside, is whether the classification into these two pre-determined categories (forefoot/heel strike) is even rational. How much importance should be placed on determining the 'natural' strike pattern? What sort of 'truth' it provides us? Some studies (Donnelly et al., 2017) have utilized this approach to classify the athletes based on their 'habitual' strike pattern, meaning that they removed all participants if they did not consistently used the same foot strike pattern for all consecutive trials. However, while this type approach to classify the athletes may seem tempting, a few details must be addressed. These are discussed next.

As mentioned above, the dichotomous classification of athletes used in some studies (Donnelly et al., 2017; Kristianslund et al., 2014) could provide a heuristic approach to the issue, however, it contains two main problems. Firstly, it diminishes the potential importance of the precise foot angle between individuals (e.g., *extreme rearfoot strikers, minor rearfoot strikers, minor forefoot strikers, extreme forefoot strikers*), and secondly, it disregards the group, which is in the literature (Kasmer et al., 2013) described as 'midfoot strikers' (a landing pattern where there is no clear heel or forefoot striking involved). The importance of understanding these subtle differences between the striking patterns may be essential when trying to understand the precise biomechanics of the foot, for instance, during running. During such activities, if the contact is made with rearfoot first, the foot and ankle complex goes through a sequence of subtalar joint pronation and supination (Hargrave et al., 2003; Neumann, 644). However, less is known, and not clearly documented in the literature, of how the foot biomechanically behaves when the initial contact is made with forefoot first (Hargrave et al., 2003). Although, it may seem rationale, in such cases, to provide such generalizations as to describe the *foot to go through a similar sequence pattern as during heel strike, but to occur in the opposite direction,* it may be, in fact, that the pronation-supination sequence among forefoot strikers is quite different compared to rearfoot strikers (Hargrave et al., 2003).

Furthermore, the midfoot strikers may, as well, have a very distinctive pronation-supination sequence pattern. The term 'flatfooted landing', which is sometimes used in the literature (Shimokochi et al., 2016), and which has a quite negative connotation, could be, in fact, associated with the midfoot striking, since it describes the lack of shock absorption that subtalar joint pronation provides. Therefore, the midfoot strikers could, indeed, be the most fragile group for injuries, due to the inadequate "roll off pattern" of the foot during gait. Analyzing the different components of this strike pattern, an assumption could be made that this strike pattern would, probably, include less time for pronation and re-supination, shorter ground contact time, as well as less time for the windlass mechanism to act optimally. If any of these speculations hold for truth, the essential question is yet to asked: does it matter in respect of injuries? Whatever the truth may be, the future studies must possibly abandon the idea of only using two categories (forefoot strike & heel strike), and rather classify the athletes into more descriptive groups.

In the current study, both the ankle and knee injuries were included in the analysis. The idea for this approach stemmed from findings of Altman and Davis (2016) whom demonstrated that different strike pattern may lead to different types of running injuries. Therefore, in the present study I wanted to test the assumption that also during cutting tasks different striking technique might result in different types of lower extremity injuries. While the findings of the present study didn't provide any further evidence for this suggestion, it is very possible that future studies, by implementing various study settings, could present results that demonstrates, for instance, the association between heel strike and knee injuries. Furthermore, some of the future studies might also show, for example, that increased plantarflexion in conjunction with forefoot striking is related with higher occurrence of ankle and foot injuries. These hypothetical, yet very potential, scenarios would, obviously, lead to a dilemma of what to consider as biomechanical risk factor, since both strike patterns would be associated with specific, yet quite different, lower extremity injuries.

A few notes in respect of the present study should be considered. Firstly, previous studies (David et al., 2017; Donnelly et al., 2017; Kristianslund et al., 2014; Yoshida et al., 2016) that demonstrated the association between elevated knee abduction moments and rearfoot striking, used a slightly different sidestep cutting task which, in fact, could be more sensitive to provoke knee abduction moment in conjunction with heel strike. For example, in the study of David and colleagues (2017) most of the subjects demonstrated forefoot striking pattern during 90° cutting, whereas in the present study rearfoot striking during the 90° task was more common. Moreover, in the present study only a small portion of athletes landed with heel during the 180° procedure. Therefore, I couldn't conduct a direct comparison between the groups based on the results of the 180° cuts, due to the overly uneven distribution of the strike patterns. Furthermore, the knee moments weren't calculated in the present study. It is only speculative, therefore, which type of strike pattern, if any, would be associated with excessive knee abduction moments, as well as elevated knee valgus angles. It is possible, that the type of 90° cutting used in this study would be, in fact, optimal – in respect of performance and injury prevention – to perform with heel strike, since the approaching angle before the change of direction was not straight (as in many of the previous studies), but oblique.

Donnelly and colleagues (2017) demonstrated that forefoot strikers presented elevated peak ankle plantarflexion moments. Fox (2018), therefore, hypothesized, that this would improve performance during cutting. Fox (2018) also suggested, based on the findings of Breine and colleagues (2014), that when the approach speed increases certain individuals might 'naturally' shift to forefoot pattern during cutting manoeuvres to counterbalance the increased knee loads. However, while this *striking technique shifting* is observed during straight-line running (Breine et al., 2014), less is known, whether this type of *technique optimization* is observed during cutting tasks (Fox 2018). Anyhow, the assumption that forefoot striking may be potentially more efficient, and even less fragile with respect to injuries, might indeed have some truth behind the claim, yet what should be realized is that these types of movement patterns are developed throughout over a long period of time and are difficult, therefore, at individual level to modify. Hence, a careful consideration should be always implemented if there is any intention to 're-program' the athlete's individual movement technique, since these types of alterations might make the athlete to more prone for injuries.

Several video-analysis studies (Boden et al., 2009; Koga et al., 2018; Montgomery et al., 2018) have confirmed that rearfoot strike is present during actual ACL injury situations. What is observed during an actual injury situation, however, is something we should not directly assume to represent the players 'natural' style of moving in most of the playing situations. Also, these types of video observations of real injury situations shouldn't lead us deductively to assume that these same athletes necessarily utilize the habitual rearfoot strike when training. Based on the current knowledge, it is impossible to determine if the observed heel strike in real injury situations is the primary factor, that affects through the whole kinetic chain and directs the knee in fragile position, or is it, in fact, that the position of the knee, hip and torso before the IC leads in such situation, where the players *chooses/is forced* to heel strike, rather than land with the ball of the foot. Understanding this sequence is essential, since it helps to determine to which of the components are the 'key drivers' that may lead to injuries.

In summary, the foot strike pattern doesn't seem to be related with acute lower extremity injuries. What we know is that rearfoot strikers exhibit higher ground reaction forces (Kulmala et al., 2013) and represent different types of muscle activation (Yong et al., 2014) during straight line running compared to forefoot strikers. On the other, previous studies have not reported any significant differences in GRFs during cutting manoeuvres between the strike patterns (Kristianslund et al., 2014; Yoshida et al., 2016). Therefore, we must be deliberative when interpreting the results of the running literature and while creating hypothesizes to understand the acute lower limb injuries during various athletic tasks. It may be, in fact, that the foot strike pattern could be mainly associated with overuse, but not acute injuries. Furthermore, more subtle biomechanical analysis is needed to truly understand the precise foot strike technique that might be related with lower extremity injuries, both acute and overuse. For instance, we must consider such details, as if the initial contact is received with the medial or lateral aspect of the heel or forefoot, since these alterations may affect on how the whole lower limb acts kinematically. In conclusion, it may be that we should abandon the idea of 'harmful' or 'fragile' landing pattern, since we don't understand which exact components, for instance, during the weight acceptance phase are 'abnormal' and which are not.

8.4 Foot Strike Kinematics

The present study showed that the only variable significantly related to lower extremity injury risk was the internal rotation of the foot (i.e., foot adduction). The foot internal rotation, however, was significantly associated only for the risk of ankle injuries. This finding is in line with the previous studies recognizing the internal rotation and inversion of the foot as risk factors for lateral ankle sprains (Kristianslund et al., 2011; Mok et al., 2011). As Donnelly and colleagues (2017) suggests, the foot position at IC, or even prior to ground contact, may indicate the injury risk for ankle injuries. The assumption, therefore, might be that the athletes at risk perform the cutting manoueuvres with more internally rotated foot, which makes them, potentially, more vulnerable for sudden inversion sprains. It should be noted, however, that there was a wide variation of foot rotation among the injured players, and as the ROC-curve analysis indicated the sensitivity and specificity of this finding was found to be poor. Nevertheless, very little is known of the kinematic risk factors for ankle injuries during cutting tasks. These novel findings, therefore, may act as a basis for future studies and provide further knowledge how to clinically assess potential risk factors for ankle sprains.

While there is a very small amount of *change of direction researches* that have documented the biomechanical risk factors associated with ankle injuries, much more research attention has been placed on to the investigations concerning the movement related risk factors for knee injuries, particularly ACL injuries. Tran and colleagues (2016) demonstrated that 'toe-in' jump landings were related with known risk factors for ACL injuries, such as elevated knee valgus angles, as well as increased tibial internal rotation angles and moments. Moreover, Jones and colleagues (2016b) found that larger internal rotation angles of the foot at IC were associated with peak knee abduction moments during the 180° cuts (similar task as used in the present study). Based on these results the authors, therefore, suggested that the players should attempt to utilize a strike pattern where the foot is close to straight, since it helps to absorb the GRFs optimally through larger muscle groups and redirect the force vector better in relation to the knee (i.e., less lateral). The results of the present study, however, didn't find significant association with internal rotation and the rate of knee injuries. Many reasons, which are discussed next, might explain these findings.

Firstly, it could be that the total amount of knee injuries was too small to provide enough statistical power to detect any significant results. Secondly, in this study all knee injuries were included in the analysis, not just ACL injuries. This makes the direct comparison to previous *ACL-injury-only* studies difficult, since different knee injury subtypes may be associated with different kinematic risk factors. Thirdly, it should be noted, for instance, that Jones and colleagues (2016b) based their foot rotation values to 'foot progression' angles *in relation to the direction the player was running* (i.e., in relation to the Global Coordination System), whereas in the present study the foot rotation angle was determined *relative to the tibia*. This slight difference might not be significant in certain cutting procedures, however, during more demanding tasks, such as the 180° cut, we can't be sure if the difference between the two measurement techniques could have affected the results. Moreover, a video-analysis study of actual ACL injuries (Koga et al., 2018) demonstrated a clear pattern where the foot was externally rotated at IC, and then internally rotated during the following 40ms. These findings may indicate that the predictive value of foot rotation at IC might not be sensitive enough, since the foot position changes significantly during the first 40ms after the initial ground contact phase.

In the present study, the ankle dorsiflexion/plantarflexion angle at IC wasn't shown to be associated with lower extremity injuries. Previous studies (Boden et al., 2009; Montgomery et al., 2018) have reported that in actual ACL injury situations the injured players demonstrated dorsiflexion in conjunction with heel strike. However, in their video-analysis study of actual ACL injuries during handball sidestep cuttings, Koga and colleagues (2018) reported quite large variation with respect to the sagittal plane ankle flexion, which indicated that there is no consistent landing pattern, but instead, that some of the injured players landed with excessive dorsiflexion, while others with highly plantarflexed ankles. Therefore, while it may be that there is an excessive dorsiflexion present at the time of an injury, the dorsiflexion angle at IC won't, however, provide any clinically relevant information to predict future injuries.

Furthermore, in respect of ankle injuries, while there is some indication that more plantarflexed ankles at IC could be more at risk to suffer lateral ankle sprain during gait and jump landings (Spaulding et al., 2003; van der Does et al., 2016), some prospective studies (Willems et al., 2005) haven't, in fact, confirmed this presumption. Willems and colleagues (2005), in fact, remarks that, for instance, the increased touchdown plantar flexion, as well as decreased range of motion of the talocrural joint, could be more likely a consequence of a previous injury, rather than a cause. Based on the findings of the present study, the ankle sagittal plane flexion angle at IC is, therefore, unlikely related to lower extremity injuries during cutting tasks. To get more comprehensive results, the future *change of direction studies* should also analyze the dorsiflexion range of motion during the stance phase, while also consider the causation of a potential previous injury when analyzing the findings.

8.5 Other Considerations

In the present study, the focus was on initial contact kinematics. However, variety of other movement related factors have been recognized previously and, therefore, should be consider when assessing the potential injury related risk factors. For instance, one of the more interesting issues that has caught a lot of research interest (Dos Santos et al., 2019), and needs a greater understanding, is the role of the penultimate step (also known as approach step, pre-turn step, before step, braking step, support foot, or preparatory step). Jones and colleagues (2016a) have suggested, that the deceleration of the center of mass, which the athlete must perform before reorienting oneself to a new direction, is done with the help of series of steps, instead of just the final, executive step. They also theorize, that with the optimal utilization of the penultimate step, particularly during large cutting angles, the athlete, in fact, may reduce most of the velocity and therefore, in consequence, alleviate the GRFs and knee abduction moments during the final contact phase – which is associated as the phase with injuries to occur (Jones et al., 2016a). A good example on the importance of the penultimate step are the long jumpers whom must adjust their preparatory steps to hit the plank optimally. Whenever conducting a study in the laboratory settings, one of the main challenges is to get the athletes to perform the cuttings 'naturally', since they always must adjust their step onto the ground reaction force plates. For instance, in this study many of the players took several *smaller* steps before hitting the force plates, so that they were able to place their foot correctly, while others had to reach for the step to hit the intended spot.

Another technical consideration is the foot placement during cutting. A wider foot placement (i.e., planted foot further from the COM) has been associated to elevated knee moments during cutting tasks (Dempsey et al., 2007; Jones et al., 2016b; Kristianslund et al., 2014). What should be noted, however, is that the wider foot placement may provide better performance during cutting tasks (Fox 2018). Therefore, with respect to these two movement characteristics (penultimate step & foot placement relative to the COM), a few details must be considered. In a rapid unanticipated game situation, where the athlete many times must compromise oneself movement strategy, the players sometimes must reach for the step heel first and the whole lower limb, consequently, extended. This may alter the lower extremity in a fragile position, as the COM and the support foot is further from the foot that executes the change of direction. Therefore, when analyzing the foot strike pattern, we shouldn't just target our interest towards the executive step, but also consider the steps prior to that (i.e., how the athlete prepares for the cutting), since it may play an important role on how the executive step is performed, and how the limb is aligned. Moreover, a careful consideration should be always implemented whenever adjusting the players technique to ensure that while the injury risk is decreased, the performance level is optimized as well.

Moreover, different sports have their own specific strategies for optimal change of direction. For instance, some authors (Bencke et al., 2013; Kristianslund et al., 2014) have stated that in handball, in which the ACL injury rates are very high, the rapid side-to-side deception movement, where the player is supported by only one leg, is more demanding than a simple directional change performed, for example, in the present study. Therefore, the findings of the present study may be difficult to generalize to certain sports where cutting tasks are performed in different ways.

8.6 Strengths & Limitations

There are some strengths and limitations of the present study that must be addressed. One of the main limitations of this study was the use of *pre-planned* execution of the cutting tasks. In game-like situations the players directional changes are many times dependent of the stimulus, such as the movements of the opponents or the ball (Sheppard & Young 2006). Previous studies, which have utilized unanticipated tasks, have reported, for instance, higher knee joint loads (Besier et al., 2001) and different trunk rotation strategies (Mornieux et al., 2014) compared to anticipated cuttings. Furthermore, some studies have also demonstrated that to perform faster change of directions, many anticipatory postural adjustments, such as the foot placement, trunk rotation and head rotation are observed (Jones et al., 2016b), which indicates that the option to pre-plan the directional change may facilitate the tasks heavily. Therefore, many disadvantages have been recognized in the use of unanticipated cutting tasks – especially when interpreting the results of these studies (Bencke et al., 2013, David et al., 2017; Fox 2018; Jones et al., 2016b).

Furthermore, in this present study the players *approach speed* wasn't controlled. In addition to the change of direction angle, the approach speed is a critical factor that may affect the knee joint loading (Dos Santos et al., 2018) and should be always considered when evaluating the findings of biomechanical studies (Fox 2018). The fact that the athletes were able to select their approach speed, as well as not have to react to stimulus, could possibly ease the tasks greatly, since the players could prepare oneself for the turn by pre-rotating the body and adding more preparatory steps (Havens & Sigward 2015a). Therefore, the findings of the present should be interpreted carefully in relation to studies with more controlled approach speeds. Dos Santos and colleagues (2018) have, in fact, stated that more biomechanical studies utilizing unplanned directional changes, as well as larger cutting angles are warranted.

Fatigue has been demonstrated to induce the athlete's proprioception (Mclean et al., 2007). This may possibly weaken the individual's ability to control the muscles and, therefore, lead to abnormal kinematics, as well as elevated loads through passive structures (David et al., 2017). For instance, Jayalath and colleagues (2018) demonstrated that fatigue affected the athletes' ankle biomechanics. In the present study, the players performed their cutting tasks only after a light warm-up, which may have helped them to align their posture better during the manoeuvres compared to a situation where the body would have been in a more fatigued state. As previous studies (Montgomery et al., 2018) have shown, many of the injuries occur in the last quarter of a match. Therefore, the future studies should potentially include some higher intensity warm-ups to increase the fatigue of the players that might help to unveil the possible abnormal kinematics more easily.

In the present study, a relatively simple foot model with three degrees of freedom was used. Previous studies (Donnelly et al., 2017; McLean et al., 2004) have suggested that non-sagittal plane ankle biomechanics could be hard to evaluate without more specific foot model. Therefore, we should deliberatively consider how accurately the inversion-eversion angles, particularly, at IC could be measured. Furthermore, the artefacts placed on the skin may cause measurement errors during fast-pace test procedures. Previous 3D-analysis studies, however, have reported good correlation of results between two test sessions of cutting tasks (Kristianslund et al., 2014). Therefore, these results could be considered reliable, especially due to the large sample size.

The cutting tasks performed in this study aimed to replicate a game-like cutting manoeuvre. However, the pivot task turned out to be much more complicated task to perform compared to the 90° procedure. This was clearly seen when the 3D-data was analysed, and every athletes' cuttings visually observed. However, what this phenomenon tells us is not clear. It could, indeed, just indicate that there is a great variance in techniques between the individuals, and that certain technique won't be associated with injuries more than some other. However, future studies should take this into account and, possibly, try to keep the technique more constant: especially, if the purpose is to apply some of these tests as for screening tools.

The present study included many strengths. Firstly, while the biomechanical studies produce valid information, and serves as the basis for creating hypothesises, Murphy and colleagues (2013) have stated, that the retrospective and case-control studies are prone to bias, since they are unable to measure potential individual risk factors before the occurrence of injury. Therefore, the prospective study design is the only way to demonstrate, whether there is any indication for causal effect between the suggested biomechanical risk factors and the occurrence of an injury.

Another notable strength in the present study was the tests used. Some of the previous studies (Dempsey et al., 2007; McLean et al., 2005; Sigward and Powers, 2007) have used a less demanding cutting angles to analyse the biomechanics of the lower extremities. For instance, the pivoting task, which is often performed, for example, in soccer (Bloomfield et al., 2007) has rarely been used in previous researches (Jones et al., 2014). Moreover, the 90° task performed in the present study involved an oblique run (instead of a straight-line run used in other studies) before the directional change. This type of angled run is often seen in some sports and it affects, for example, to the body position and direction of the GRF vectors compared to straight approach runs (Dos Santos et al., 2019).

Furthermore, one of the strengths of this study was also the large number of athletes (both floorball and basketball players), which increases the reliability of the results. Additionally, in this study both sexes were included. While girls tend to suffer far more knee injuries than boys (Swenson et al., 2013), with respect to the ankle injuries this trend is not so clear (Murphy et al., 2013). Future studies, however, should consider investigating also the possible sex differences of biomechanical risk factors associated with ankle injuries. Previous studies, in fact, have shown that there is some indication of differences between males and females in respect of the foot and ankle kinematics (Kernozek et al., 2005; McLean et al., 2007).

8.7 Future Implications

In what follows, some suggestions are offered for researches conducting studies in the future. The future studies should go beyond just investigating the kinematics of the initial contact, and rather analyze the whole foot landing phase between 0% and 50% of stance – weight acceptance phase where non-contact ACL injuries, for instance, are suggested to occur. Practically speaking, this would tell us more of how the foot behaves through the stance phase. It could be, in fact, that the foot alignment at IC won’t provide enough information to analyse the biomechanical risk factors for injuries. Therefore, future studies should also consider of analysing the kinetics (e.g., moments, work, power) related to the foot landing pattern.

Furthermore, future studies should also consider a more detailed foot model, since it helps to analyse, particularly, the non-sagittal plane foot kinematics. Especially, the foot frontal plane kinematics provides interesting research topic, since previous video-analysis studies (Koga et al., 2018; Walden et al., 2015) are not in line of how the foot and ankle act in conjunction with dynamic knee valgus. A more detailed kinematic data could, therefore, provide important elements to design injury reduction interventions.

Moreover, studies in the future should be ambitious enough to study the biomechanics of the lower extremities by using extreme cutting angles, such as pivot tasks, and utilize unanticipated circumstances. Additionally, future studies should also explore the foot landing kinematics with athletes representing different sports, while using various cutting manoeuvres typical in those sports. Also, the present study focused only on acute injuries, therefore, other studies should evaluate the potential relationship between the foot landing pattern and overuse lower limb injuries.

Additionally, in the present study the possible association between the kinematic risk factors and injury risk was investigated by analyzing several separate kinematic variables. The future studies with larger study populations, therefore, should aim to examine the possible cluster of factors that in combination may increase the risk for injuries.

Lastly, as previous findings (Almeida et al., 2015; Bergstra et al., 2015; Hollander et al., 2014) have demonstrated the footwear affects, to varying degrees, on foot strike pattern. I, therefore, courage the future researches to investigate the potential association between the athletes’ footwear and strike pattern. This type of information could, for instance, reveal the possible acute response of different footwear on striking technique.

8.8 Conclusions

The conclusions of this master's thesis are the following:

1) The foot landing pattern (heel strike vs. forefoot strike) wasn't associated with lower extremity injuries among young team athletes.

2) The internal rotation of the foot was the only variable that was significantly related with lower limb injuries. However, this association was only observed in respect of ankle injuries.

3) Subtle differences between the cutting procedures, such as the approaching angle, may effect on how the athletes perform the cuttings and what type of landing pattern they utilize. Therefore, direct comparisons between the studies with respect to the kinematics should be made deliberatively.

4) There is a large variation in respect of the movement technique between individuals. This was seen both when visually observed the trials from the 3D-data, as well as when analyzing the quantitate data. Most importantly, however, based on the findings, no specific technique pattern could be described particularly 'injurious' (i.e., prone for injuries).

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