

Bachelorarbeit

Does flexible pes planus, determined by navicular drop test, increase the risk of ACL injury in post-adolescent subjects?

A literature review

**Zehnder Daniela S08257065
Maurerweg 2
CH- 8400 Winterthur**

**Departement: Gesundheit
Institut: Institut für Physiotherapie
Studienjahr: 6. Semester
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Betreuende Lehrperson: Arjen van Duijn**

**Bachelor
Thesis**

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Zehnder Daniela (PT08a) S08257065

Zurich University of Applied Sciences
School of Health Professions
Institute of Physiotherapy
6. semester

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Tutor: Arjen van Duijn

Forward

This Bachelor thesis presents a literature review, in which the author strived to better understand the role of the medial longitudinal arch of the foot in anterior cruciate ligament injury and to use these findings to contribute to a successful prevention of the same.

For the evaluation of methodological quality, a specific hypothesis was defined and comparable studies were searched. In the course of literature analysis, the author realised that these studies were not conclusive enough to deduce practical applications. Therefore, literature search was extended looking for pioneering works related to the same topic. The additional results are summarized in the Chapters 4.2 and 4.3 but were not compared with respect to methodological quality because of highly heterogeneous methodology.

Abstract

Introduction. Non-contact anterior cruciate ligament (ACL) injuries are very frequent in young athletes. In spite of rigorous research in the etiology of non-contact ACL injuries, screening parameters and prevention programs do not show the expected effects. The excessive flattening of the medial longitudinal arch of the foot represents a possible risk factor because the adherent pronation seems linked to internal rotation of the tibia. Internal rotation in the knee potentially loads the ACL. The aim of this literature review was to determine whether asymptomatic flatfoot (flexible pes planus), measured by navicular drop (ND) test, is a risk factor for non-contact ACL injury in post-adolescent athletes.

Methods. CINAHL, medline (via Ovid SP) and Cochrane databases were searched for relevant literature between January 1990 and December 2010.

Results. Eight retrospective observational studies investigating the correlation between ND test, a measure of foot pronation, and history of ACL injury were found. Five supported a significant difference in ND values between subjects with ACL injury history, but three refuted it. Additional studies investigated correlations of ND with other lower limb alignments and kinematic parameters. Last but not least, some studies used orthotic devices to search for effects of foot pronation on the alignment and kinematics of the lower limb.

Conclusions. Navicular drop (ND) test by Brody (1982) is no sensible screening parameter for athletes at risk. Nevertheless, dynamic navicular drop measured by motion analysis seems to play a role in injury mechanisms leading to non-contact ACL injury. Further research is needed to understand the relevance of dynamic control of foot pronation during landing or cutting tasks which put the athletes at risk for non-contact ACL injury.

Keywords. Navicular drop, flexible pes planus, overpronation, hyperpronation, anterior cruciate ligament, risk factors.

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1 Introduction

The foot establishes ground contact. It is built out of 26 bones and includes a large number of joints. Its function is based on passive structure but also strongly affected by active control. As such it is highly adaptable and succeeds in compensating for proximal structural abnormalities and functional deficiencies. On the other side, the complexity of the foot is also a hazard. In a closed kinetic chain structural and functional deficiencies can be transferred to proximal body parts.

Williams, McClay and Hamill (2001) found that low-arched and high-arched runners showed significantly different injury localisations in the lower extremity. High arches were associated with strain on the lateral leg and low arches were related to medial strain. While high-arched runners had more bone injuries such as tibial stress fractures, low-arched runners showed more soft-tissue injuries. Additionally, low-arched runners suffered nearly twice as many knee injuries.

A medial soft-tissue structure in the knee is the anterior cruciate ligament (ACL). The health directorate of Zürich¹ (2009) reports 10'000 to 12'000 ACL-injuries annually in Switzerland of which 73% are sports related². Calculative estimations done by the health directorate of Zürich (2009) assess costs of 200 to 250 Millions CHF annually due to knee injuries with ACL rupture. Additionally, many people suffer from osteoarthritis of the knee 10 to 20 years after injury date, independent of conservative or surgical treatment.

Research has been interested in evaluating the risk factors for ACL rupture in the last two decades. ACL injury often occurs in actions like landing, cutting or pivoting (Susta, O'Mathùna, Parkinson, 2010) which implies that certain sports as football, handball or basketball put athletes at risk. Faulty neuromuscular control and female gender are believed to increase risk for ACL injury (Hewett et al., 2005; 2006). Findings point out a great number of extrinsic and intrinsic risk factors and presume a multifactorial etiology of ACL injury (Griffin et al., 2006). The question is about influenceable factors with a relevant effect on risk probability. In order to successfully screen athletes at risk and to create efficient prevention programs for non-contact ACL injury more definite

¹ German: Gesundheitsdirektion des Kantons Zürich

Numbers are based on injury statistics published by the compulsory accident insurance between 1997 and 2001.

² Included are people recorded in the compulsory accident insurance. As a result, children, students, people in retirement and self-employed persons are excluded.

statements about intrinsic risk factors are required. In particular, prospective studies are scarce (Hewett et al., 2005; Östenberg & Roos, 2008; Engebretsen et al., 2010) and foot structure and function have often been neglected in risk evaluation.

Landing, cutting or pivoting task are high-impact maneuvers which require safe deceleration of the body in complex game situations. Therefore, the absorption of ground-reaction forces presents an important factor in preventing ACL injuries.

Regarding the foot, the medial longitudinal arch plays an important part in ground-reaction force absorption during gait (Kapandji, 2006). Further, subtalar joint pronation which is a component of the flattening of the medial longitudinal arch has been linked to internal rotation of the tibia (Kirtley, 2006) and internal rotation of the knee again has been associated with a common ACL injury mechanism which is characterised by knee valgisation (Koga et al., 2010).

The aim of this literature review was to determine whether asymptomatic flatfoot (flexible pes planus), measured by ND test, is a risk factor for non-contact ACL injury in post-adolescent athletes. If this was true ND test would be a fast and low cost mean to screen for athletes at risk and prevention programs could be more specified by focussing on foot function. The author hypothesized that greater ND values are representative for excessive pronation in the subtalar joint and that this excessive motion would lead to kinematics³ of the lower limb loading the ACL during high-impact maneuvers which would finally result in ACL-rupture.

³ The branch of mechanics that studies the motion of a body or a system of bodies without consideration given to its mass or the forces acting on it.

2 Theoretical background

2.1 Anatomical background

2.1.1 Anatomy and function of the longitudinal arch

In conformity with Schünke, Schulte, Schumacher, Voll and Wesker (2005) the longitudinal arch is built by passive and active structures. The passive structures consist of bones and ligaments. As shown in Figure 2.1 the tarsal and metatarsal bones create an arch in sagittal view. This arch is highest through os metatarsi II, os cuneiforme intermedium, os naviculare and os calcaneus. More lateral sagittal sections show decreasing arch heights. Soft tissue of the lateral foot has ground contact, whereas the normal medial foot shows a hollow space. Hochschild (2008) defines the bony limitations as follows: In medial view, the bony limitations are the processus medialis calcanei proximally and the caput ossis metatarsalis I distally. The os naviculare represents the highest point of the bony arch in medial view. In lateral view, the bony limitations are the processus lateralis calcanei and distally the caput matatarsalis IV and V. The os cuboideum represents the highest point of the lateral longitudinal arch

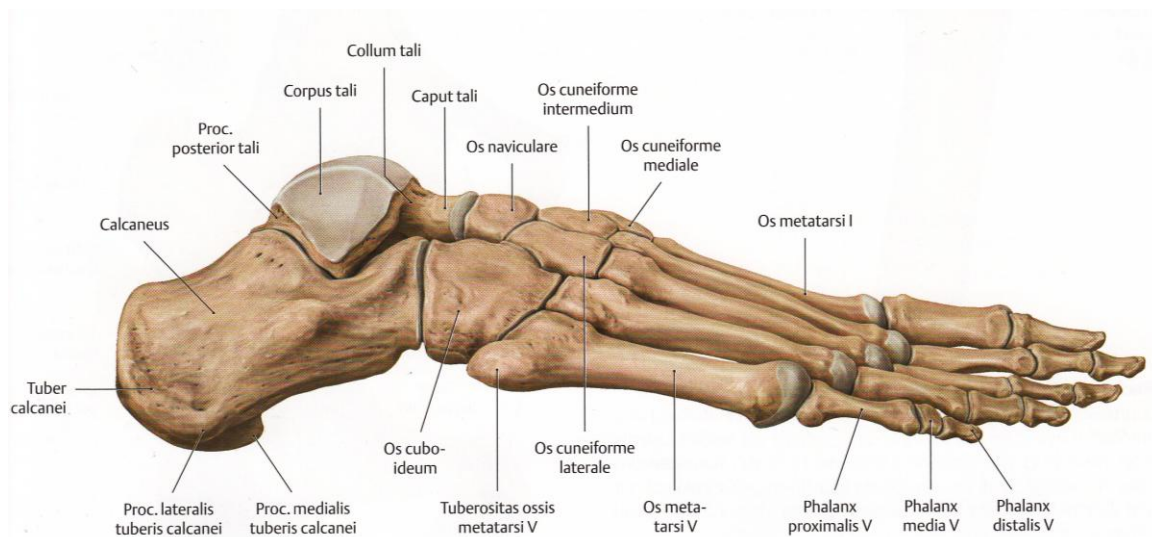


Figure 2.1 Bones of a right foot (lateral view)

The bony arch is held by various ligaments. Schünke et al. (2005) and Hochschild (2008) both postulate that the most relevant ones are the aponeurosis plantaris, the lig. plantare longum and the lig. calcaneonaviculare plantare (Figure 2.3).

Hochschild (2008) defines the aponeurosis plantaris as a flat fascia with maximal thickness in its central part. It is fixed at the processus medialis tuberis calcanei and distally it diverges in its fasciculi longitudinalis and finally integrates in the lig. metatarsium transversum superficiale. The functions of the aponeurosis plantaris are the protection of plantar muscles, the stabilisation of fat tissue on the sole and to the support of the longitudinal arch.

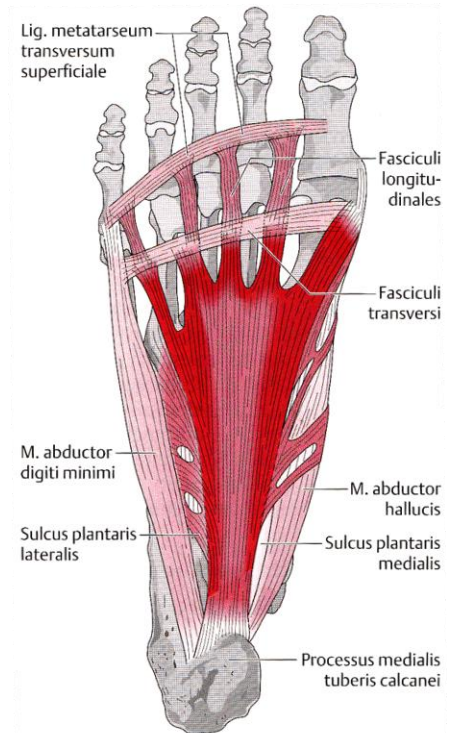


Figure 2.2 Aponeurosis plantaris (dark red)

The lig. plantare longum originates at the medial and lateral tuber calcanei and elongates until the os cuneiforme and further until the basis of os metatarsi I-V. The lig. calcaneonaviculare plantare is embedded in the capsule of the talocalcaneonavicular joint. It is covered by a cartilaginous coating and articulates with the caudal part of the caput tali.

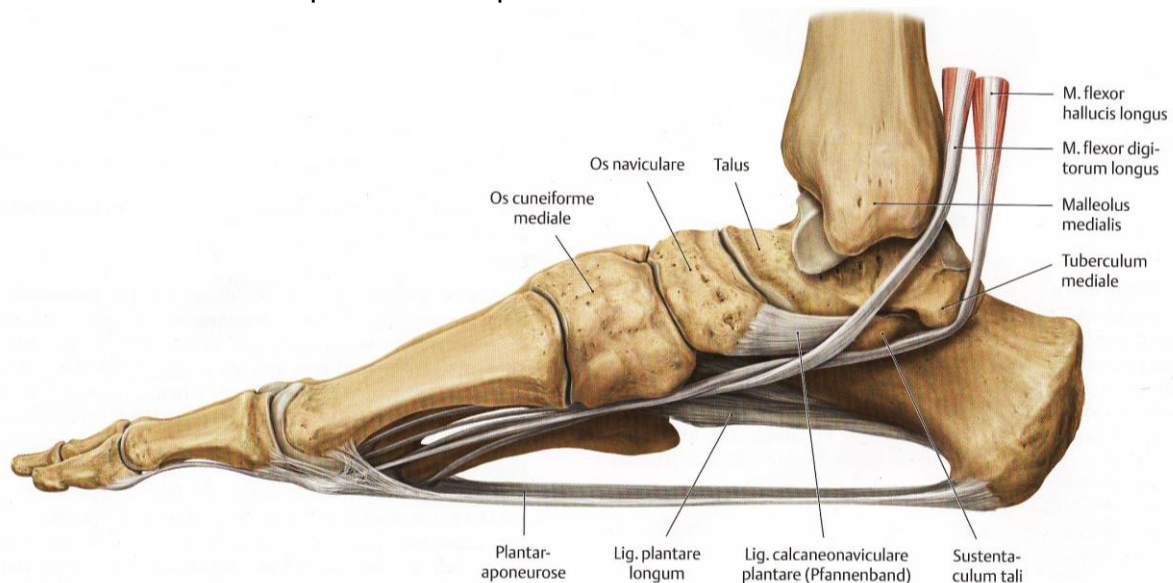


Figure 2.3 Passive structures of the longitudinal arch (medial view)

Hochschild (2008) explains that ligamental structures of the foot provide major proprioceptive data. This afferent information in combination with visual and vestibular inputs is required for adequate coordination during gait.

Due to their anatomical course (Figure 2.3), the tendons of mm. flexor hallucis longus and flexor digitorum longus support the longitudinal arch (Schünke et al., 2005). Active stabilisation consists of mm. abductor hallucis, flexor hallucis brevis, flexor digitorum brevis, quadratus plantae and abductor digiti minimi. Pursuant to Hochschild (2008) the list can be supplemented with mm. tibialis posterior and peronei brevis et longus. Furthermore, the mm. extensores digitorum longus et brevis and extensores hallucis longus et brevis exert a traction on the metatarsal insertion of the aponeurosis plantaris via dorsal extension of the big toe (Figure 2.4) which stabilizes the longitudinal arch during terminal-stance and pre-swing⁴.

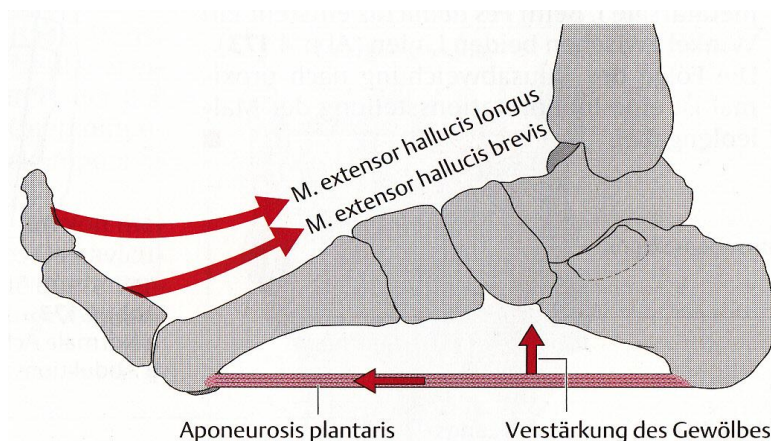


Figure 2.4 Contraction of the mm. extensorum digitorum longus /brevis and extensorum hallucis longus /brevis exerts traction on the aponeurosis plantaris.

According to Schünke et al. (2005) the longitudinal arch enables adaptation of the foot to ground unevenness and absorption of vertical loading forces. During dynamic gait a flattening of the longitudinal arch is normal. Hochschild (2008) describes an inversion position of approximately 3-4° during heel strike and a subsequent eversion until approximately 7° during loading response. During the rest of stance phase inversion is restored and a more or less neutral position is maintained during swinging.

⁴ Phases of the normal gait cycle

2.1.2 Anatomy and function of the anterior cruciate ligament (ACL)

The cruciate ligaments guide movement of tibia and femur. The anterior cruciate ligament (ACL) limits maximal extension of the knee joint and controls ventral shear forces of the tibial plateau produced by muscle contraction and body mass displacement. Shear forces depend on magnitude and direction of muscular tractions, on co-contraction activity and on the external load on the limb. Knee flexion moments and quadriceps contraction stress the ACL. Ischiocrural activity on the other hand reduces strains on the ACL, for example during squatting. (Brinckmann et al., 2000).

According to Hochschild (2008) the ACL crosses the knee from proximal-dorsal-lateral on the lateral femur condylus to distal-ventral-medial on the tuberculum intercondylaris of the tibia. Hochschild presumes that the ACL is stressed with internal rotation of the tibial bone. Further, Hochschild postulates that together with posterior cruciate ligament the ACL assists in frontal stabilisation of the flexed knee.

2.2 Flexible pes planus

2.2.1 Definition of flexible pes planus

As per Hochschild (2008), a flexible flatfoot is characterised by an inclination angle of metatarsal I smaller or equal to 18° instead of approximately 25° and a downward displacement of the os naviculare which makes it impossible to place two fingers under the medial foot in standing position. As a result, os calcaneus and os metatarsale I move apart and the ligamental structures sustaining the arch are elongated. Further, the talus moves in plantar and medial direction, entailing hindfoot eversion and forefoot abduction. Finally, these changes cause internal rotation of the malleoli.

Hochschild (2008) elucidates that thick soles can wrongly lead to flatfoot diagnosis. The soles consists of interbedded fat tissue and absorbs vertical pressure forces like a pillow. If it is thicker than usual it decreases the hollow space of the medial foot in standing position although the bony structures of the longitudinal arch are perfectly normal.

Kuhn, Shibley, Austin and Yochum (1999) defined flexible pes planus as: „[...] A foot with an observable medial arch while in a non-weight-bearing position (sitting or recumbent) and the absence of this arch while in a weight-bearing position

(standing). [...] The reduction of the medial longitudinal arch results from plantar deviation (inward or medial rotation) of any of these three articulations: the talocalcaneal joint, the talonavicular joint, and the naviculocuneiform joint [...].“ (p 221) In other words the flattening of the medial longitudinal arch implies pronation of the subtalar joint.

This review includes studies investigating flexible flatfeet or excessive pronation as a potential risk factor for ACL injury. Other forms of flatfeet as described with „rigid“, „posttraumatic“ or „acquired“ or related to neurological or rheumatoid diseases, to Ehler-Danlos- Syndrom, Marfan syndrom or posterolateral tibial tendon dysfunction are not taken into consideration.

2.2.2 Foot pronation

Foot pronation is a complex three dimensional movement involving multiple joints. More precisely, motion components are eversion, dorsiflexion and abduction. Eversion of the hindfoot occurs in the frontal plane, dorsiflexion of the ankle joint in the sagittal plane and abduction of the forefoot in the transversal plane (Kapandji, 2006).

2.2.3 Clinical assessment of flexible pes planus

Since pronation involves motion in different directions at different joints, strategies for assessment of the subtalar joint position and motion are highly heterogeneous. Established clinical parameters to describe foot structure are calcaneal eversion (also referred to as heel valgus), navicular drop (ND), navicular height and assessment tools based on footprints like the arch index (AI), the valgus index (VI) or the Chippaux-Smirak index (Billis, 2007; Stavlas, 2005; Razeghi, 2001). Kuhn et al. (1999) used radiographic imaging to determine talocalcaneal angles in anterior-posterior and lateral view as well as the talar pitch angle, which is defined as the angle between an axis line drawn through the talus and a horizontal line representing the weight-bearing surface. With an electronic pedobarograph or pressure sensing mat it is possible to capture dynamic plantar pressures at different instants of the stance phase during walking. Other authors proposed the contact force ratio, which is determined by midfoot loading divided by loading of the total contacted foot area except the toes (Leung, Cheng, Zhang, Fan and Dong, 2004).

2.2.4 Navicular drop (ND) test

In this review navicular drop (ND) has been chosen to characterise foot structure and function. ND was first described by Brody (1982). It consists of locating the navicular tuberosity while the subject is standing in bipedal stance. Vertical distance to the ground is measured two times. First with the foot placed in subtalar joint neutral position and second in relaxed standing. ND is defined as the difference of the two values recorded.

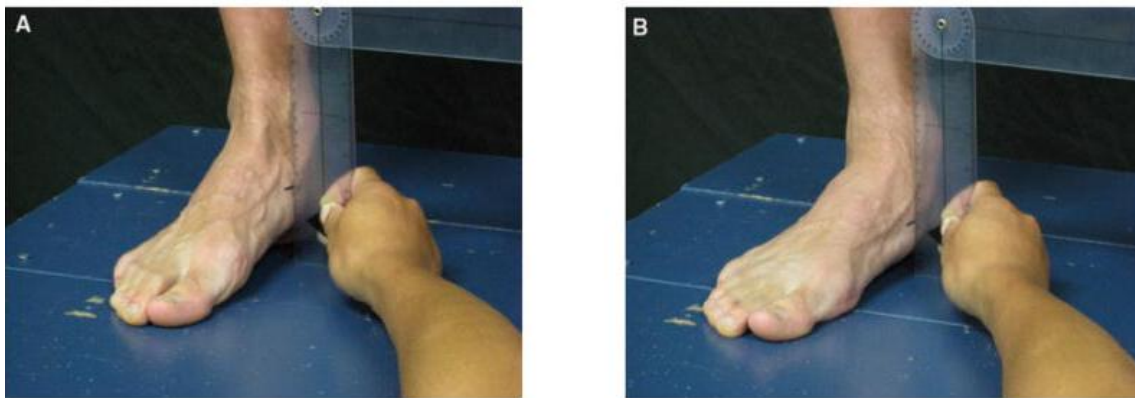


Figure 2.5 Measurement of navicular drop as the change in navicular height from standing neutral (A) to standing relaxed (B)

Billis et al. (2006) attributes good intra-tester reliability⁵ to ND (Brody, 1982) and found significant correlations of ND with AI and VI. He considers ND a simple and reliable measure of foot posture, which is more closely related to dynamic rearfoot function and lower limb dysfunction than footprints and more susceptible to detect arch height differences than the AI. Several authors gave evidence on high intra-tester reliability. In the study of Sell et al. (1994) reported intra-class correlation coefficient (ICC) for intra-tester reliability of 0.83; Shrader et al. (2005) presented ICCs for intra-tester reliability from 0.90 to 0.98.

Unfortunately, ND is not without controversy. Palpating the navicular tuberosity and defining subtalar neutral position possibly creates inter-tester⁶ bias. Sell et al. (1994) reported an ICC of 0.73 for inter-tester reliability. Shrader et al. (2005) found ICCs ranging from 0.67 to 0.92 and states that inter-tester reliability is improved when subjects absolved some training in holding subtalar joint neutral

⁵ Concordance between consecutive measurements performed by the same assessor (tester)

⁶ Inter-tester reliability means the concordance between measurements performed by different assessors

position and also when navicular tuberosity was repalpated in relaxed standing (accounting for skin marking error).

Additionally, data on normal ND range is not conclusive. Nielsen et al. (2009) screened previous literature and found that mean values among healthy adults ranged from 3.6 to 8.1 mm in the original version of the ND test and from 7.3 to 9.0 mm in modified versions. The upper limit for normal (physiological) ND was defined 15, 13, and 10 mm respectively by different authors (Brody, 1982; Beckett, Massie; Bowers, Stoll, 1992; Mueller, Host, Norton, 1993).

2.3 Non-contact ACL injury

2.3.1 Definition

In accordance with Shimokochi and Shultz (2008) ACL injuries during functional activities excluding any external forces other than the ground reaction force are defined as non-contact ACL injuries. McNair, Marshall and Matheson (1990) and Boden, Dean, Feagin and Garrett (2000) defined 70% and 72% respectively of all ACL injuries as non-contact.

2.3.2 ACL loading and injury mechanisms

The following Chapter refers to an extensive review performed by Shimokochi and Shultz (2008). The authors gathered interviews data about and video tapes of non-contact ACL injuries. Furthermore, they summarised in vitro and in vivo studies as well as computer simulations evaluating direct ACL-loading produced by joint loading, muscle forces and functional weight-bearing tasks.

Common playing situations for injury are landing from a jump and sudden deceleration of the body while running with or without change in direction. Peak strain measurements correlate with peak ground reaction forces and occur immediately after heel strike (approximately 40 ms after initial contact). Evidence supports an injury mechanism with multiplane loading of the knee joint during weight-bearing activities with the ipsilateral foot touching the ground. In particular, the combination of valgus and internal knee rotation moments during shallow knee flexion (ca. 5 - 30°) highly strain the ACL. Another well documented injury mechanism that consists of valgus loading combined with external tibial rotation moments is probably linked to ACL impingement at the intercondylar notch (Figures 2.6/7). Hyperextension plus internal or external tibial rotation clearly put ACL at risk too. The role of quadriceps contraction in loading the ACL is still disputed. On the one hand, quadriceps contraction might cause great anterior tibial shear forces and load the ACL, especially at low knee flexion angles when posterior tibial shear forces by the ischiocrural muscles are retrained most and the angle of infrapatellar tendon and longitudinal axis is maximized. On the other hand, injury related tasks are thought to produce a posterior directed ground reaction force pushing the tibia backwards which would unload the ACL.

2.3.3 Dynamic valgus/ valgus loading/ valgus collapse

Several authors observed an injury mechanism whose main characteristic is knee valgisation (knee abduction). This frontal plane motion is coupled to movements of the limb in the transversal plane. Whereas earlier observational studies pointed at external tibial rotation (Hewett et al., 2005; Ireland, 1999), more recent investigations detected internal rotation of the tibia during the essential phase of landing (Koga et al., 2010). Koga et al. (2010) analysed ten videos of female handball and basketball players during ACL injury and found that valgus loading was coupled with internal tibial rotation in the first 40 ms after ground contact. The authors then observed external rotation of the knee and hypothesized that at this point the ACL was already ruptured. As mentioned before, anatomical orientation of the ACL and in vitro studies further support that the ACL is loaded in internal rather than external rotation of the knee. In a literature review, Quatman and Hewett (2009) stated that rotational motion accompanies frontal plane motion of the knee during valgus collapse. Figure 2.8 shows their perception of this injury mechanism and makes clear that the direction of knee rotation is not specified.

Krosshaug et al. (2007) stated that the injury mechanism of valgus collapse occurred more frequently in female than male basketball players.

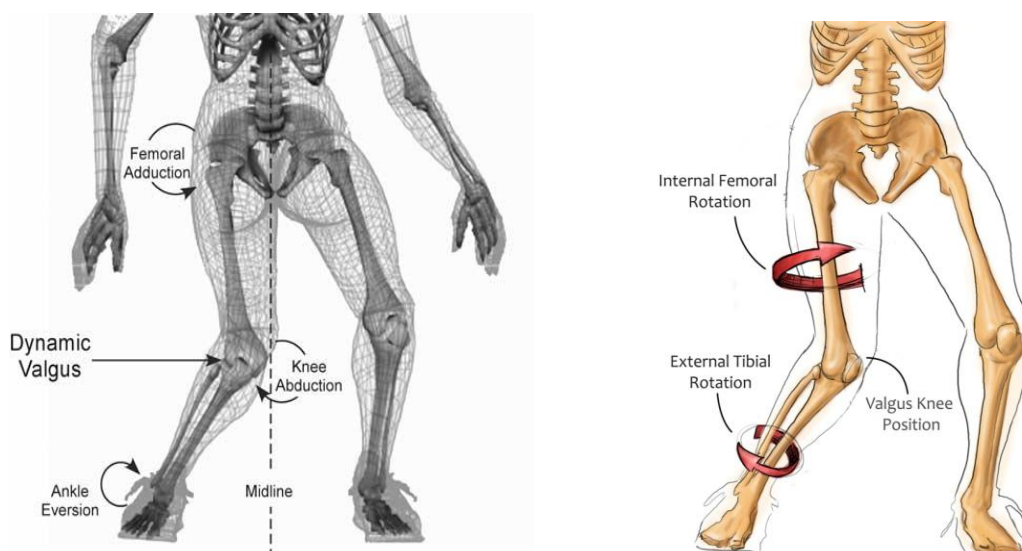


Figure 2.6 Hewett et al. (2005) defined dynamic valgus as the position or motion, measured in three dimensions, when the distal femur moves toward and the distal tibia away from the midline of the body.

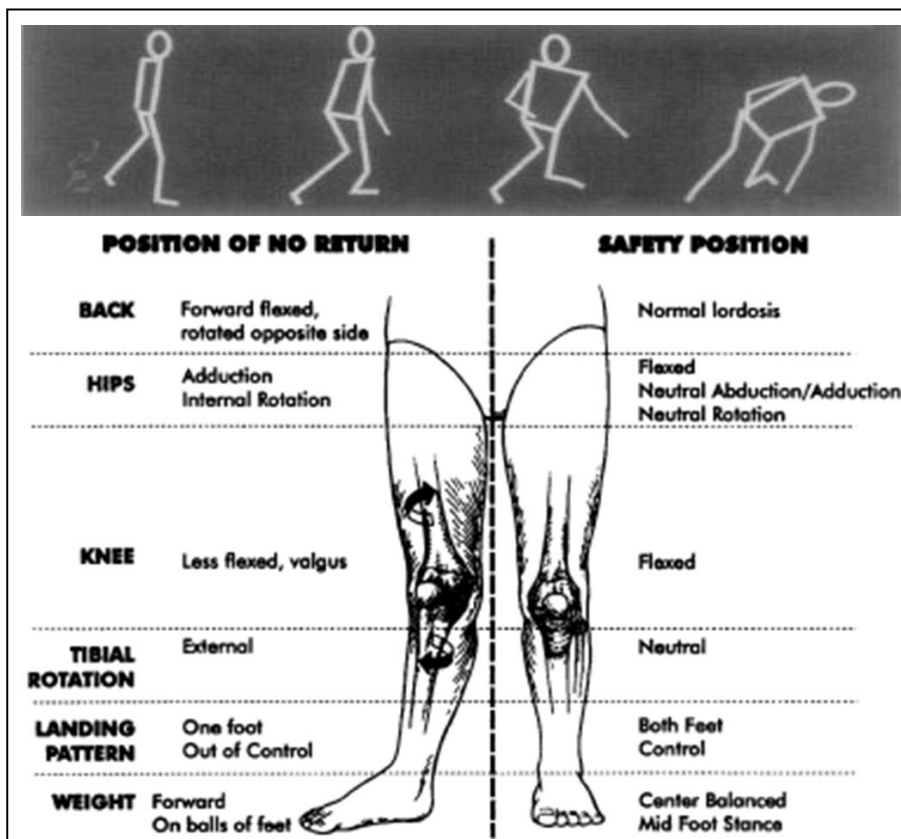


Figure 2.7 Position-of-no-return on the right limb (lower) and sequence of body positions during ACL tear (upper) described by Ireland (1999).

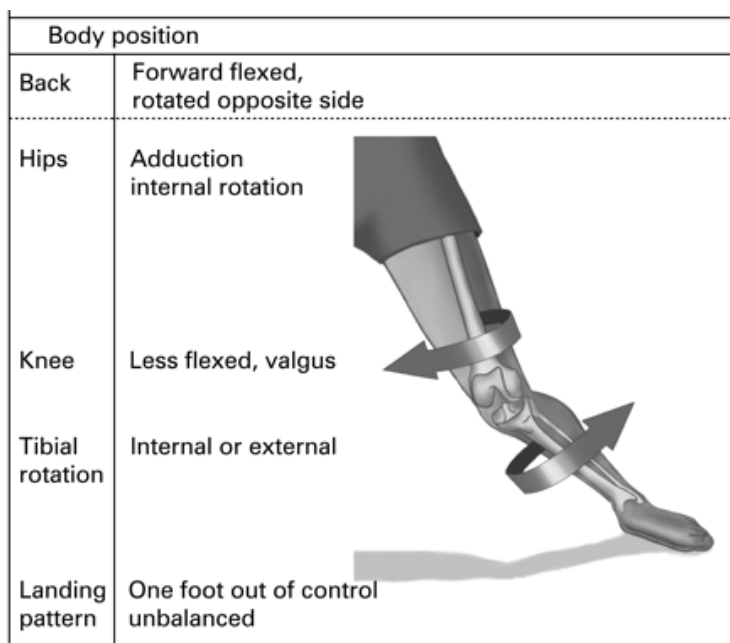


Figure 2.8 Valgus collapse: a common ACL injury mechanism in women which includes internal or external rotation of the tibia.

2.3.4 Tibial internal rotation

Whenever tibial internal rotation is tracked by three-dimensional motion analysis, it is important to know whether it was measured with respect to the femur. If the answer is yes, tibial internal rotation represents internal rotation of the tibiofemoral joint. If the study does not specify tibial internal rotation, movements in the articulations of the foot or hip could have led to the same results.

Figure 2.9 shows internal rotation of the whole limb in space due to foot pronation. Notice the neutral position of the tibiofemoral joint although the patella is directed more medially than normal.

Hence, tibiofemoral internal rotation implies tibial internal rotation but tibial internal rotation does not always mean internal rotation of the tibiofemoral joint.

Also, tracking the patella in space and describing internal rotation does not prove internal rotation in the tibiofemoral joint.

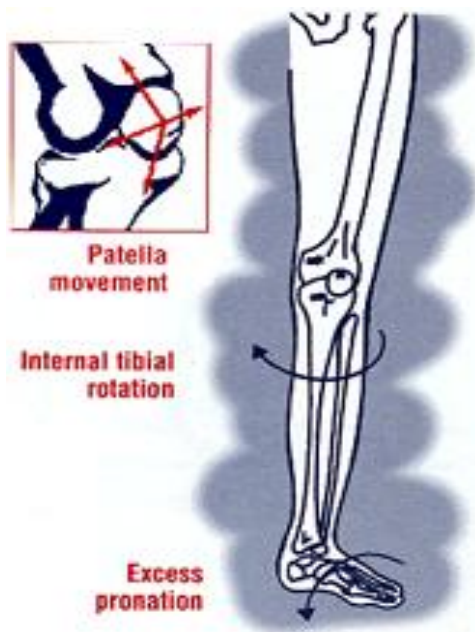


Figure 2.9 Internal rotation of the limb due to excessive pronation in the foot.

2.4 Previous research on the consequences of flexible pes planus

A lot of research in overuse injuries in runners has been undertaken in the last three decades and pes planus has been regarded as a potential risk factor. A prospective observational study performed by Kaufman, Brodine, Shaffer, Johnson and Cullison (1999) analysed foot structure and range of motion in 449 trainees at the Naval Special Warfare Training Center in Coronado, California and showed that subjects with pes planus or pes cavus had a two-fold risk of sustaining stress fractures (overuse injuries).

Medial tibial stress syndrome, posterior tibialis tendinitis, achilles tendinitis, iliotibial band friction syndrome, plantar fasciitis have been linked to increased or prolonged pronation (Dirix, Knuttgen and Tittel, 1988). But it is important to know that some authors negated increased risk of lower extremity injury in subjects with pes planus (Cowan et al., 1993; Gilardi, 1985; Burns et al., 2005, Michelson et al., 2002). Some even explain that more flexibility can be protective and that rigidity, as in pes cavus, puts subjects at risk. A review of literature in the databases PubMed and Medline between 1966 and 2006 came to the conclusion that although variables related to excessive pronation have often been mentioned in combination with the incidence of specific injuries; the impact characteristics remained in debate (Ryan et al, 2006). Flexible pes planus has also been related to anterior knee pain and low back pain. Lakstein, Fridman and Kosashvili (2010) used data from the medical examinations of 97'279 Israel Defense Force recruits aged between 16.5 and 19.3 years. In 2008, they published a study which supported an association of moderate and severe pes planus with a nearly two-fold rate of anterior knee pain and intermittent low back pain. In 2010 they reused these medical records and affirmed a significant correlation between flexible ($p=0.013$) as well as rigid ($p=0.0001$) pes planus with anterior knee pain in both female and male recruits. The theoretical model underlying these investigations was that excessive pronation resulted in tibiofemoral compensations and thus increased patellofemoral compression (Tiberio, 1987). Comparing 100 subjects with chronic or recurrent mechanical low back pain with 104 subjects without low back pain revealed lower arch heights and greater ND values in the healthy control group (Brantingham et al., 2006).

3 Methods

3.1 Data sources

CINAHL, medline (via Ovid SP) and Cochrane databases were searched for relevant literature between January 1990 and December 2010.

3.2 Designs

Both observational and experimental studies were included. Computer models or literature reviews like Master theses or dissertations were excluded.

3.3 Participants

The mean age of the participants was required to be at least 17 years (post-adolescent), since the significance of flexible pes planus in children and adolescents is discussed controversially. A low arch or flat foot has been traditionally regarded as undesirable but a large cross-sectional study performed by Stavlas et al. (2005) showed that normal development of the longitudinal arch continues until late adolescence. Based on footprints of 5866 children between seven and 17 years old, they postulate that abnormal arch heights tend to be compensated during growth when subjects get older.

Participants were either healthy or asymptomatic despite of their abnormal foot structure. Studies including participants with pathological conditions other than ACL injuries were excluded. This was the case for subjects with patellofemoral pain syndrome, patellar luxation, osteoarthritis, traumatic rupture or degeneration of the tendon of m. tibialis posterior and neurological disorders affecting the limb.

3.4 Search strategy and keywords

First, databases were searched for literature relating to the direct association of ND and non-contact ACL injury. The primary keywords were “anterior cruciate ligament injuries” AND “navicular drop”. Complementary, databases were searched for studies and review articles on risk factors of ACL injury. Therefore, the keywords “risk factors” and “anterior cruciate ligament injuries” were used. The precise hypothesis (H) to be tested was:

- H₁: ND is a predictor of ACL injury history

Secondly, the keywords “anterior cruciate ligament injuries” AND “foot orthos* OR anti-pronation tap*” were used to answer the second hypothesis:

- H₂: Foot orthoses and taping aiming at limiting pronation reduce ACL injury rate

In a third step, databases were searched for studies investigating on the interaction between ND and kinematical patterns of the knee which have been associated with ACL injury mechanisms. Those include tibiofemoral internal and external rotation, tibial internal rotation (definition in Chapter 2.3.4), knee abduction (valgisation) and anterior tibial translation. Since “valgus collapse” as described by Quatman & Hewett (2009) includes hip internal rotation, studies revealing effects of ND on hip rotation were considered as well. To make it concrete, the below-listed hypotheses were phrased.

Primary keywords are presented in brackets.

- H₃: ND correlates with static alignment measurements that potentially pre-load the ACL
(“navicular drop” AND “alignment”)
- H₄: ND is greater in females and hence, explains greater ACL injury rates in females (same as for H₂ but only those with gender specific groups)
- H₅: Foot orthoses and taping aiming at limiting pronation change static alignment that potentially pre-load the ACL
(“foot orthos* OR anti-pronation tap*” AND “alignment”)
- H₆: Foot eversion or pronation captured by 3D-motion analysis during landing and cutting tasks correlate with knee kinematic patterns that are commonly related to ACL injury
(“navicular drop” AND “deceleration maneuver”)
(“biomechanic* AND knee” AND “deceleration maneuver”)
- H₇: Foot orthoses and taping aiming at limiting pronation change knee kinematics during landing and cutting tasks
(“foot orthos* OR anti-pronation tap*” AND “deceleration maneuver”)

In order to increase the sensitivity of the search, synonyms or similar terminology were added to the primary keywords mentioned above (Table 3.1). Moreover, links to related articles and the references of the relevant studies were searched manually.

Table 3.1 Keywords

MeSH: Medical Subject Headings (in Ovid SP)

Primary keyword (combined with Boolean phrase AND)	Synonyms and related terminology (combined with Boolean phrase OR)
navicular drop	navicular height OR pes planus OR flexible pes planus OR overpronation OR hyperpronation OR calcaneal eversion OR eversion OR foot deformities, longitudinal arch OR (MeSH) ankle joint
anterior cruciate ligament injuries	(MeSH) Anterior cruciate ligament OR (MeSH) anterior cruciate ligament injuries
risk factors	Risk, prevention OR (MeSH) risk factors OR proneness
biomechanic* AND knee	knee valgus OR knee abduction OR valgisation OR valgus loading, tibial internal rotation OR knee rotation OR hip adduction OR hip internal rotation OR (MeSH) biomechanics OR (MeSH) knee joint OR kinematic* OR kinetic* OR joint moment*
foot orthos* OR anti-pronation tap*	orthotic* OR orthopaedic footwear OR wedge* OR insole* OR foot tap*
deceleration maneuver	jump* task OR single leg landing OR stop and go task OR cutting task OR (MeSH) task performance and analysis
alignment	Q angle OR tibiofemoral angle OR knee valgus OR knee abduction OR tibial internal rotation OR knee hyperextension OR genu recurvatum OR hip internal rotation

3.5 Evaluation of methodological quality

Results for the first hypothesis (H_1) were tested for methodological quality by a predetermined list of criteria (Table 3.2). Criteria were selected based on a quality evaluation described by Trees et al. (2007) and the explanations of Mann (2003) in a research article with the title “Observational research methods. Research design II: cohort, cross-sectional, and case-control studies”. Maximal score is 48 points. Quality evaluations are archived in the appendix (8.1.3-10).

Results for the second step of search were highly heterogeneous in design, sample, interventions and outcomes. Meticulous quality assessment would have gone beyond the scope of this Bachelor thesis.

Table 3.2 Criteria to assess the methodological quality of observational retrospective studies (search results for the main hypothesis H_1). Further explanations are given in the appendix (Chapter 8.1.2).

Criteria	Max. points
1.1 Hypothesis clearly stated	2
1.2 Hypothesis clearly answered	2
2 Sample	(12)
2.1 sample population defined	2
2.2 recruitment	2
2.3 sample size justified	2
2.4 entry criteria and exclusions stated and justified	2
2.5 control group matched or randomised	2
2.6 control group is comparable to sample (table 1)	2
3 Data collection and data processing	(14)
3.1 accurate description of data collection	2
3.2 accurate description of statistical analysis	2
3.3 reliability and validity of measurements	2
3.4 reproducibility of results / primary results presented in a table	2
3.5 adherence to methodology	2
3.6 missing data	2
3.7 informed consent	2
4 Blinding	(10)
4.1 subjects ignore purpose	2
4.2 subjects ignore group membership	2
4.3 assessors ignore purpose	2
4.4 assessors are independent	2
4.5 assessors ignore group membership	2
5 statistical analysis	(6)
5.1 alpha level	2
5.2 presentation of statistical results is complete and comprehensible	2
5.3 control of confounding factors / discussion of limiting factors	2
6 external validity	2
	48

4 Results

Seven hypotheses (H_1 - H_7 listed in Chapter 3.4) were stated in order to answer the study question. Figure 4.1 presents the most important sub-questions asked and illustrates the Chapters in which the results are going to be presented.

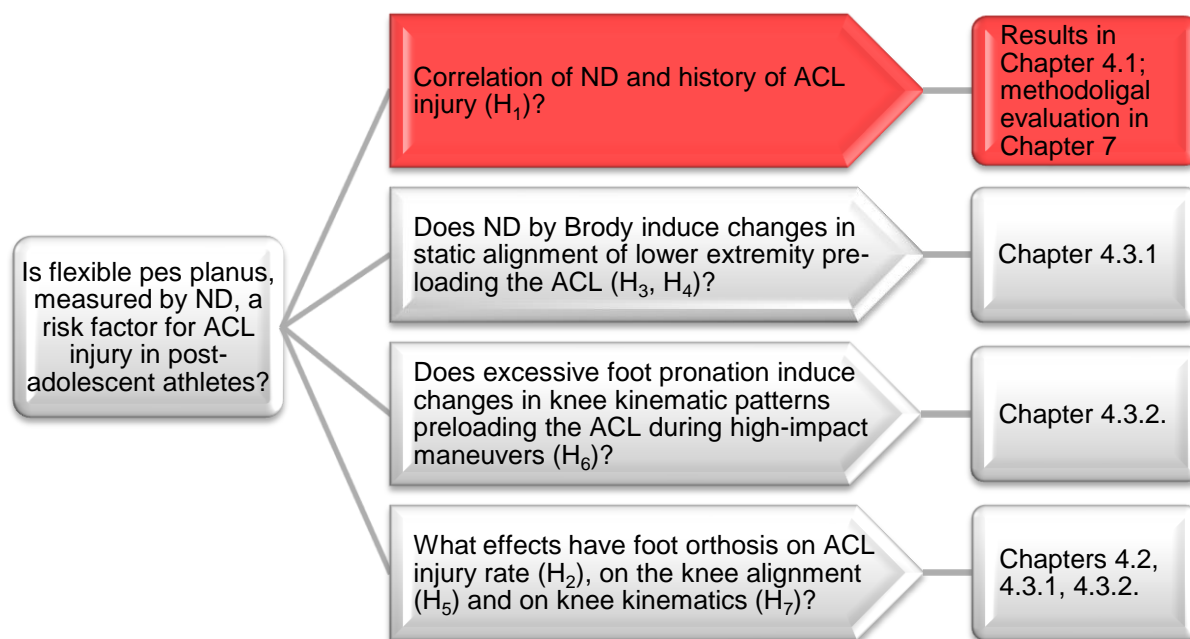


Figure 4.1 Content and presentation of the search results

■ : main hypothesis (H_1); methodology was evaluated accurately

4.1 ND is a predictor of ACL injury history (H_1)

Several observational studies investigating the correlation of greater ND and ACL injury have been identified. An overview is given in Tables 4.1/2. All of them were retrospective cohort studies and compared participants with and without history of ACL injury. All of them searched for significant differences (alpha-level <0.05) of ND between groups. Four of them approved a positive correlation of excessive ND and ACL injury history, and three refuted it. Whereas early studies tended to support a correlation between ND and ACL injury history (1992/4/6), later investigations revealed contradictory. Allen et al. (2000) differed from the others, because a metrecom⁷ was used to measure navicular height instead of palpation by an assessor.

⁷ FARO Medical Technologies Inc, Lake Mary, FL

Table 4.1 Search results for the main hypothesis (H_1): Studies investigating the correlation of ND and ACL injury history.

Ref.	First author	Publication year	Title
[1]	Beckett M.E.	1992	Incidence of hyperpronation in the ACL injured knee: a clinical perspective
[2]	Woodford-Rogers B.	1994	Risk factors for ACL injury in high school and college athletes
[3]	Loudon J.K.	1996	The relationship between static posture and ACL injury in female athletes
[4]	Smith J.	1997	Role of hyperpronation as a possible risk factor for ACL injuries
[5]	Allen M.K.	2000	Metrecom measurement of navicular drop in subjects with anterior cruciate ligament injury
[6]	Hertel J.	2004	Lower extremity malalignments and ACL injury history
[7]	Jenkins W.L.	2007	ACL injury in female and male athletes: the relationship between foot structure and injury
[8]	Kramer L.C.	2007	Factors associated with ACL injury: history in female athletes

Beckett, Massie, Bowers and Stoll (1992) selected 50 subjects with a history of ACL injury and a mean age of 22.9 years and performed ND tests bilaterally. More than half of them (27 of 50) reported non-contact injury mechanism. 50 randomly assigned patients and staff members without history of lower extremity pathology served as controls. Beckett et al. (1992) proved that groups were comparable in terms of age and that no significant differences existed between left and right sides, nor between gender. Conversely, the ACL injured group showed significantly larger ND measurements. Consequently, the authors suggest that excessive ND has a pre-loading effect via internal rotation of the tibia and may increase the risk of ACL injury.

A study of Woodford-Rogers, Cyphert and Denegar (1994) measured ND, change in calcaneal alignment (thigh-foot-ankle) and anterior tibial displacement (using a KT-1000 knee arthrometer). Within a two year period, two samples were recruited. First, 14 ACL injured male football players with a mean age of 19.1 years and second, six female gymnasts and two female basketball players with mean age of 19.5 years. For each group equal numbers of controls that were matched for sports and level of competition (in football also position) were selected. Woodford-Roger et al. (1994) report a correlation of ND, anterior drawer laxity and ACL injury. Whereas 60% of variance between ACL injured group and control group could be explained by those outcomes in

women, ND and anterior knee joint laxity only accounted for 20% of variance in men! The authors conclude that ND and knee joint laxity might be useful screening parameters, but also that additional factors not assessed in this study probably contribute to ACL injury risk.

Similarly, the hypothesis of Loudon J.K., Jenkins and Loudon K.L. (1996) was that certain postural characteristics tend to preload ACL during activity and increase proneness to injury. They assessed seven static parameters of the lower extremity and allocated each subject in predetermined categories named “normal”, “high” or “low” for each parameter. Parameters were pelvic position, femoral anteversion, hamstring length, standing sagittal knee extension, standing knee angle in the frontal plane, ND and rearfoot position. The ACL injured group included 20 female athletes participating in basketball, volleyball, tennis or soccer two or three times a week. The control group was matched for age, gender, height, weight and activity level. Group membership could be predicted by excessive ND, excessive subtalar joint pronation and excessive sagittal knee position (genu recurvatum⁸). Whereas from the controls only six had ND values greater than 9 mm, 15 of the 20 ACL injured female athletes were allocated in the “high” category. Loudon et al. (1996) reasoned: “[...] There is a strong association between non-contact injuries to the anterior cruciate ligament in female athletes and females who display a standing posture of genu recurvatum with subtalar joint overpronation [...].” (p 95)

In 1997, Smith, Szczerba, Arnold, Martin and Perrin contradicted these findings. They measured ND in 14 subjects with history of non-contact ACL injury and 14 subjects without, including equal numbers of women and men and matching the controls for age, height and weight. In the ACL injured group, two subjects had suffered bilateral ACL injury and were excluded. The authors compared ND values of the uninjured leg and a side-matched leg in the control group and found no correlation between ND and group membership. Nonetheless, Smith et al. (1997) emphasised the importance of future prospective studies and suggested that static ND measures may not be representative of dynamic subtalar joint behaviour.

⁸ Knee hyperextension / back knee

Allen and Glascoe (2000) aimed at reducing measurement bias in ND test and used a metrecom, an electromechanical digitizer that measures three-dimensional change between the two positions of the navicular bone. Intra-tester reliability was excellent (ICC=0.90) and the authors emphasized that metrecom measurements are not affected by skin movement over the navicular bone. Allen and Glascoe (2000) examined 18 (12 male, 6 female) subjects with history of ACL injury and 18 controls that were matched by age and gender. Sample population was older (mean age approximately 30) than the before mentioned studies (mean ages between 18.1 and 26.5 years). The results of this study showed that both the uninjured and injured limb of the ACL injured subjects had significantly greater ND values than the controls.

The findings of Hertel, Dorfman and Braham (2004) underpin the hypothesis H_1 too. Hertel et al. (2004) searched for static parameters related to history of ACL injury. Ten women and ten men with history of ACL injury as well as 20 matched (for side, gender, age, height, weight) controls were recruited on a large university campus and ND, pelvic tilt, active hip internal and external rotation and quadriceps angle were measured. The ACL injured subjects showed significantly greater values for ND and pelvic anterior tilt. These results were independent of gender. In other words, they were consistent if women and men were analysed separately. Statistics revealed that subjects with ND greater than 8 mm had a 20 fold probability of having sustained ACL injury compared to subjects with a ND inferior to 6.3 mm. Nevertheless, ND and anterior pelvic tilt explained only 42% of variance associated with ACL injury history and the authors concluded that further research is needed to assert risk factors.

Later investigations failed to fortify the hypothesis H_1 . Jenkins, Killian, Williams, Loudon and Raedeke (2007) reported ND mean values of 10.6 mm in the ACL injured group and 10.0 mm in the controls. In a cross-sectional design, they had recruited participants in basketball and soccer teams of one university. 68 soccer players (34 female and 34 male) and 37 basketball players (19 female and 18 male) had been recruited and subsequently, ACL status was assessed. 14 women and two men reported previous ACL injury and the other participants were used as controls. Since the difference in ND was not significant, the authors suggested focussing future research on lower extremity structures other than the foot.

Eventually, Kramer, Denegar, Buckley and Hertel (2007) published a study in which they tested a broader selection of parameters which would possibly differ in subjects with and without history of ACL injury. Included were parameters describing lower extremity alignment, flexibility patterns and postural control. Kramer et al. (2007) also recorded whether participants previously sustained ankle sprains. After examining 33 physically active females and 33 controls, they found no significant differences in ND values. Nevertheless, 41 feet of the ACL injured participants and only 27 feet of the controls had visually assessed pes planus ($X_2=6.36$, $p=0.04$). Furthermore, ACL injured participants reported significantly more previous ankle sprains ($X_2=5.93$, $p=0.02$). For regression analysis each limb was categorized into a “low”, “middle” or “high” group according to each parameter. Statistics revealed significant association of the Beighton laxity scale⁹ and the Ober’s test¹⁰ with both history of ACL injury as well as history of ankle sprain. Kramer et al. (2007) highlighted the consistent trend in literature that general laxity is a risk factor for ACL injury. On the other hand, the authors suggested that lateral ankle sprains could alter subtalar joint stability and hence, affect the kinetic chain more proximally.

⁹ increased general laxity

¹⁰ decreased laxity of iliotibial band and m. tensor fascia latae

Table 4.2 Correlation of ND and ACL injury history: An overview

CS: cross-sectional, CC: case-control, pro: prospective, retro: retrospective, ACLi: ACL injured, ACLni: ACL not injured, f: females, m: males, r: right limb, l: left limb, Correl.: significant correlation of ND and ACL injury

□: results did not support H_1

■: results supported a correlation of ND and ACL injury history

Ref	Design	Sample size and gender	Main results Mean values \pm SD	Correlation of ND and ACL injury history	Quality score
[1]	CC	50 ACLi (11 f, 39 m) 50 ACLni (18 f, 32m)	\emptyset ND(ACLi-r): 13.0mm \pm 4.4 \emptyset ND(ACLi-l): 12.7mm \pm 4.0 \emptyset ND(ACLni-r): 6.9mm \pm 3.2 \emptyset ND(ACLni-l): 6.9mm \pm 2.8	F(1.196)=129.6, p=0.01	18
[2]	CC	22 ACLi (8f, 14 m) 22 ACLni (8f, 14m)	\emptyset ND(ACLi): 8.4mm \pm 4.2 \emptyset ND(ACLni): 5.9mm \pm 2.4 Significant intergroup differences were also found for anterior knee joint laxity.	$\chi^2=7.45$, p<0.01 (ND and anterior knee joint laxity considered)	25
[3]	CC	20 ACLi (f) 20 ACLni (f)	ND>9mm(ACLi): 15 ND>9mm(ACLni): 6 6mm>ND<9(ACLi): 4 6mm>ND<9(ACLni): 14 Genu recurvatum was also found a significant intergroup discriminator.	$\chi^2=7.14$, p=0.008	26
[4]	CC	14 ACLi (7 f, 7 m) 14 ACLni (7 f, 7 m)	\emptyset ND(ACLi-r): 6.3mm \pm 3.1 \emptyset ND(ACLi-l): 7.2mm \pm 4.2 \emptyset ND(ACLni-r): 6.2mm \pm 2.6 \emptyset ND(ACLni-l): 6.8mm \pm 3.2	p>0.05	23
[5]	CC	18 ACLi (6 f, 12 m) 18 ACLni (10 f, 10m)	\emptyset ND(ACLi): 10.5mm \pm 4.0 \emptyset ND(ACLni): 8.1mm \pm 2.8	p<0.05 (t-test)	26
[6]	CC	20 ACLi (10 f, 10 m) → 24 injured limbs 20 ACLni (10 f, 10 m) → 24 side-matched limbs for control	\emptyset ND(ACLi): 8.4mm \pm 2.5 \emptyset ND(ACLni): 6.8 mm \pm 2.7 Significant correlation factor r for ND (r=0.38, p=0.02), and also for pelvic tilt (r=0.39, p=0.04)	p<0.05 (t-test), r ² =0.14, p=0.004 (association!)	26
[7]	CS	16 ACLi (14 f, 2 m) 89 ACLni (39 f, 50 m)	\emptyset ND(ACLi): 10.6mm \pm 4.3 \emptyset ND(ACLni): 10.0mm \pm 4.4	p=0.88 (t-test)	24
[8]	CC	33 ACLi (f) 33 ACLni (f)	\emptyset ND(ACLi): 6.3mm \pm 2.9 \emptyset ND(ACLni): 6.5mm \pm 2.7 Significant differences between groups were found for visually assessed foot type (ACLi: 41 pes planus, ACLni: 27 pes planus) and generalized joint laxity and history of ankle sprain.	p=0.66 (t-test)	24

4.2 Foot orthoses and taping aiming at limiting pronation reduce ACL injury rate (H₂)

Only one study has been found. Jenkins, Raedeke and Williams (2008) recorded knee injury rates (number of knee ligament injuries divided by number of games and practices within a given season) of all members of the women's basketball team at one university. From 1992 to 1996, participants did not wear orthoses. From 1996 to 2005, all wore over-the-counter shoe inserts with a standard 3° rearfoot post and a standard arch fill during all basketball activities. Results revealed that participants in the control group have a 7.14 fold risk of sustaining ACL injury compared to those wearing orthoses. In total, 155 athletes were recruited over a period of 13 years. In spite of limitations owing to historical sampling of the control group, Jenkins et al. (2008) concluded: "[...] Foot orthoses contribute to a decrease in the knee ligament injury rate for female collegiate basketball players [...]" (abstract)

4.3 Effects of excessive navicular drop on knee alignment and kinematics

4.3.1 Does ND induce changes in static alignment of lower extremity pre-loading the ACL?

Hypotheses: ND correlates with static alignment measurements that potentially pre-load the ACL (H₃). ND is greater in females and hence, explains greater ACL injury rates in females (H₄). Foot orthoses and taping aiming at limiting pronation change static alignment that potentially pre-load the ACL(H₅):

ND values are similar between genders (Nguyen & Schultz, 2007; 2009; Shultz, Nguyen and Levine, 2009; Moul, 1998) and do not explain that females have a seven fold risk of sustaining ACL injury (Jenkins et al., 2007).

Further, evidence links ND to anterior knee laxity measured by knee arthrometer (Trimble, Bishop, Buckley, Fields, Rozea, 2002) and isolated studies suggested that antipronation taping (Figures 4.2/3) and orthotic devices could reduce quadriceps angle and tibial internal rotation in static standing posture (Hadley, Griffiths., Griffiths, Vicenzino, 1999; Kuhn, Yochum, Cherry, Rodgers, 2002).

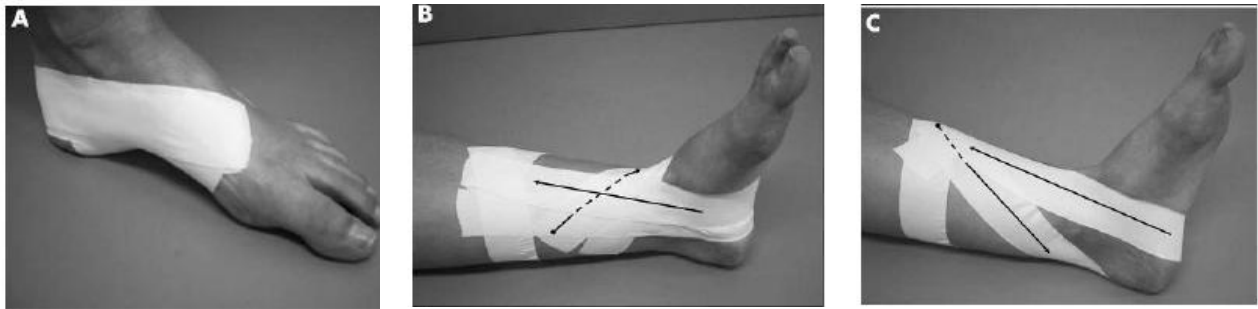


Figure 4.2 A) low dye taping B) reverse six technique C) calcaneal sling technique

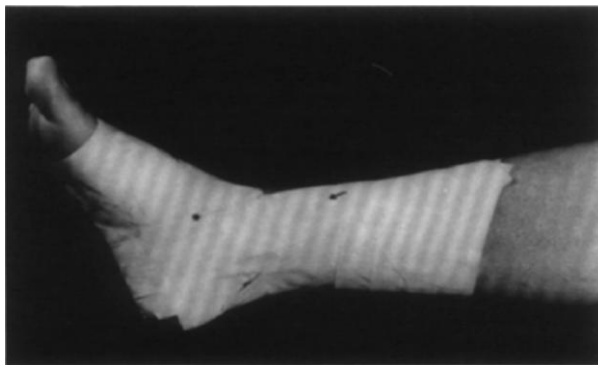


Figure 4.3 The augmented low dye taping consists of low dye taping plus reverse six technique plus calcaneal sling technique.

4.3.2 Does excessive foot pronation induce changes in knee kinematic patterns pre-loading the ACL during landing and cutting tasks?

Hypotheses: Three-dimensional motion analysis of landing and cutting tasks reveals correlations between excessive pronation of the foot and knee kinematic patterns loading the ACL (H_6). Additionally, foot pronation captured by three-dimensional motion analysis during landing and cutting tasks is greater in females than in males and hence, explains greater ACL injury rates in females.

Kernozek, Torry, Van Hoof, Cowley and Tanner (2005) recorded lower extremity kinematics and kinetics in 15 female and 15 male healthy recreational athletes performing a two-legged landing from a 60 cm elevated hang bar. The main differences between genders occurred in frontal plane movement. In females Kernozek et al. (2005) observed significantly greater maximum values of foot pronation (0.91° for men, 20.85° for women) and knee abduction¹¹ (0.66° for men, 24.85° for women) during total landing period ($p < 0.05$). Regrettably, the authors did not test for association between maximal foot pronation and maximal

¹¹ Valgisation

knee abduction. Their suggestion that increased range of motion in frontal plane movement of the foot serves energy absorption can be questioned because vertical ground reaction forces were greater instead of smaller in women.

Similar findings were made by Ford, Myer, Smith, Vianello, Seiwert and Hewett (2006). They examined frontal plane excursions between matched female and male athletes when performing single-leg drop landings from a 13.5 cm high box. The sample group consisted of eleven female and eleven male basketball or soccer players. Three-dimensional motion analysis revealed that females landed with greater knee abduction angles at initial contact ($F=20$, $p<0.001$) and showed greater maximum values for foot eversion ($F=8.3$, $p=0.009$) and knee abduction ($F=14.5$, $p<0.001$) during landing period. When subjects were asked to land more laterally, these differences were maintained but the difference in foot eversion was less dominant.

Mitchell et al. (2008) suspected that “[...] improper foot and ankle kinematics may influence more proximal joints and may also be a factor which underlies increased susceptibility to ACL tears [...]”. (p 134) They hypothesized that female collegiate soccer players which have more medial loading patterns during gait would show greater ankle eversion and knee abduction during drop vertical jump. Hence, they captured barefoot plantar pressures during normal gait in 33 female collegiate soccer players and allocated each foot to a lateral (34 legs) or medial (32 legs) loading group. Subsequently, motion analysis was performed during two-legged drop landing from a 31 cm high box with adjacent maximum vertical jump. Group affiliation neither correlated with ankle eversion nor with specific knee kinematics during the drop vertical jump. While Mitchell et al. (2008) concluded that “no effect of foot and ankle biomechanics exists on the landing mechanics of female soccer player”, the author of this literature review postulates that medial foot loading patterns during gait does not correlate with overpronation (ankle eversion) during drop vertical jump and that the lack of specific knee kinematics in the group with medial loading during gait therefore is due.

Hypothesis (H₇): Foot orthoses and taping aiming at limiting pronation change knee kinematics during landing and cutting tasks.

Joseph et al. (2008) examined ten NCAA¹² Division I female athletes, thereof six basketball, three volleyball players and one soccer player. The repeated-measures crossover design included two conditions: 1) with shoes only and 2) with additional bilateral full-length 5° medial posts. The task consisted of a two-legged drop landing from a 31 cm high box with adjacent maximal vertical jump. In the posted condition, three-dimensional motion analysis revealed a significant reduction of knee valgus ($p < 0.01$) at initial contact and at maximum as well as significantly smaller mean ankle eversion angles at initial contact ($p < 0.01$) and at maximum ($p = 0.039$). Joseph et al. (2008) considered medial posting a potential instrument to reduce ACL injury risk. Moreover, they had previously measured ND by Brody and found that greater ND positively ($p = 0.08$) correlated with greater maximum eversion during drop landings.

Jenkins, Williams, Durland, Adams and O'Brien (2009) also used three-dimensional motion analysis to compare lower extremity kinematics in different conditions. Those were 1) shoes only 2) custom-made orthoses and 3) over-the-counter orthoses. Twelve healthy female physical therapy students were analysed performing a single-legged landing after jumping with 75% of maximal height. Jenkins et al. (2009) noted that the ACL is the primary stabilizer of the knee against rotation and hypothesized that orthotic devices decrease transverse plane motion in the knee and hip. Results showed that custom-made orthoses reduced tibial internal rotation by 3.09° ($p = 0.031$) compared to condition 1); this effect was propagated proximally and reflected in a reduction of hip internal rotation of 1.16° ($p = 0.07$). Contrariwise, over-the-counter orthoses reduced internal rotation of the hip only (-2.09°, $p = 0.02$). The authors concluded that both medial postings succeeded in reducing internal rotation in the limb, but did so in different joints. Jenkins et al. (2009) also explicated that participants with abnormal foot function would give deeper insight in the real potential of foot orthoses.

¹² National Collegiate Athletic Association

A different approach consists of using orthotic devices to simulate abnormal foot alignments. Tillman et al. (2003) hypothesized that medial posting limits pronation and consequently reduced internal tibiofemoral rotation. They recruited seven healthy young women with normal foot alignments and analysed lower extremity kinematics during single-legged drop landings from a 43 cm high platform. Three conditions were compared: 1) neutral 2) medial and 3) lateral posted orthotics. After an unsuccessful testing period with 4° posts, 8° posts were used and tibiofemoral internal rotation revealed significantly smaller in the medially posted condition ($p \leq 0.03$) compared to the lateral posted condition. Medial posting resulted in a 3.1° reduction of tibial internal rotation compared to neutral condition. Tillman et al. (2003) also advanced the view that medial posts could reduce the risk of knee injuries by limitation of excessive pronation.

Summary

Video analysis of landing supported that healthy females land with increased knee valgus and foot pronation/eversion. An attempt to show that more medially located foot loading during walking correlates with lower extremity kinematics during landing tasks failed. Medial posts affected transverse plane motion of the limb. However, different orthotic devices acted at different joints (ankle complex, knee, hip) and it remains unclear whether the reduction of internal rotation prevents ACL loading.

All studies listed in this Chapter are cross-sectional and included healthy subjects without foot malalignments or history of lower extremity injury.

5 Discussion

5.1 Main results

The purpose of this literature review was to investigate whether ND by Brody is a risk factor for ACL injury in post-adolescent athletes. The main hypothesis (H_1) suggested ND as predictor of ACL injury history. Eight studies were found between 1990 and 2010. While five of them supported H_1 , three did not. Although the majority of all subjects assessed (130 participants out of 201 in total) revealed a significant correlation between ND test by Brody and history of ACL injury, the evidence is not strong enough to assert the validity of ND test as a screening factor to detect athletes at risk.

5.2 Methodological quality and limitations

Quality assessments for the eight studies presented in Table 4.1 as well as a summary of the relevant information are archived in the appendix (Chapter 8.1.3-11). A selection of interesting points is being presented here.

5.2.1 Study designs were all retrospective

All eight studies are observational, retrospective and measured foot structure after ACL injury already occurred. The problem with retrospectivity is that ND could have been different at the time of injury. Regrettably, time between ACL rupture and measurement is mostly unknown (Table 5.1), treatment strategies were heterogeneous and no information is available about sports, activity level, pain or other lower extremity injuries at the time when ACL injury happened. Therefore, retrospectivity represents a major limitation.

Table 5.1 Time space from ACL injury to measurement and treatment procedure

□: results did not support H₁

■: results supported a correlation of ND and ACL injury history

Ref.	Time space from ACL injury to measurement	Treatment procedure
[1]	–	–
[2]	– (some subjects were still in an acute state after ACL injury, so that bilateral stance was not possible and ND testing occurred on the uninvolved side)	–
[3]	2 years	surgical: 8 conservative: 12
[4]	–	surgical: 14 conservative: 2
[5]	–	surgical: 16 conservative: 2
[6]	7 years to 3 months before testing	all surgical
[7]	–	all surgical
[8]	5 years	all surgical

5.2.2 Controlling for side differences is essential in retrospective designs

Since most of the ACL injuries in the context of this review are unilateral, it is reasonable to suspect that, assuming that ND influences injury risk, ND values are different in the involved limb compared with the uninvolved limb of the subject. As a consequence, testing ND in the uninvolved limb would lead to faulty conclusions. In this review, the study of Woodford-Rogers et al. (1994) is concerned. Another way of reasoning suggests that differences in ND in subjects with history of ACL injury are post-injury or post-surgical adaptations. This would attack all studies assessing the involved limb (Table 5.2).

Table 5.2 Side differences in ND

✓: performed, ✓✓: no significant difference (uniform sample or statistical test), ACLi: ACL injured group

□: results did not support H_1

■: results supported a correlation of ND and ACL injury history

Ref.	Control for side differences for ND in the control group	Control for side differences in ACLi	On which leg ND was measured in the ACLi?
[1]	✓✓	✓✓	both limbs
[2]	✓✓	–	uninvolved limb
[3]	–	–	involved limb
[4]	✓✓	✓✓	both limbs
[5]	✓✓	✓✓	both limbs
[6]	– (both sides measured but evaluation missing)	– (both sides measured but evaluation missing)	involved limb
[7]	✓✓	✓✓	mean value
[8]	–	–	mean value

Fortunately, these arguments were countered by several studies which proved that ND is symmetric in both subjects with unilateral ACL injury and controls (Beckett, 1992; Smith, 1997; Allen, 2000; Jenkins, 2007). Controlling for side differences in both groups reduces potential bias. Of course the most elegant way to eliminate these questions would be a prospective study design.

5.2.3 Definition of sample population was absent or insufficient

Defining the sample population is essential in ACL injury risk research. Previous literature showed that the range of potential risk factors is large and prioritisation difficult. For foot structure too, evidence is not uniform and doubts still remain. These uncertainties are possibly caused by insufficient accuracy in the determination of the population. Table 5.3 illustrates that specifications about population were insufficient.

Risk factors could be different for various age cohorts, genders and sports. Possibly, ND is relevant only in a certain population. Because the longitudinal arch evolves during life time (Stäheli et al., 1987), age plays a role. Moreover, different sports use different movement strategies, create different situations putting athletes at risk and have their specific training elements (Cowley, Ford, Myer, Kernozek and Hewett, 2006). It can be hypothesized that sports like basketball and volleyball bring more medial (vertical) landings, whereas in

soccer, badminton or tennis lateral or backward cutting tasks represent the major risk for ACL tear. Different sports also use different materials which on their side considerably affect movement strategies. In Badminton for example, the knee opposite to the racket-hand side tended to sustain ACL injury during single-leg landing, whereas the knee on the racket-hand side was prone to ACL injury during side or backward stepping (Kimura, Ishibashi, Tsuda, Yamamoto, Tsukada, Toh, 2010). In summary, sports, activity level and gender possibly evoke different injury mechanisms and ND is only linked to one specific. Further, injury mechanism was not always pre-defined or at least recorded. Table 5.4 shows that three studies exclusively included subjects which reported non-contact injury mechanism. One study included both contact and non-contact injury mechanism but controlled for potential bias. More irritating is that the four most recent studies did not give sufficient information concerning this aspect. In contact injury mechanism, external force amplitude and direction, instead of foot alignment and kinematics, might play the major role. The author thinks that subjects which sustained contact injury do not represent the population at risk for non-contact ACL injuries. Therefore, the lack of information about injury mechanism can be considered a major limitation.

Table 5.3 Minimal criteria for the definition of sample population include age, gender, activity level and sports.

□: results did not support H₁

■: results supported a correlation of ND and ACL injury history

Ref.	Age (y)	gender	Activity level (h per week)	Sports
[1]	–	females and males	–	–
[2]	High school and college	females and males	–	Soccer, basketball, gymnasts
[3]	–	females	Participate in sports 2 or 3 times per week	Soccer, basketball, volleyball, tennis
[4]	–	females and males	–	–
[5]	–	females and males	–	–
[6]	–	females and males	–	–
[7]	–	females and males	–	Soccer, basketball
[8]	–	females	(physically active)	–

5.2.4 Participant numbers were acceptable but selection not rigorous enough

None of the eight studies justified sample size. When no calculation was performed, the author expected a sample size of approximately 30 participants per group in the case-control studies and several hundreds or thousands for cross-sectional studies. Only two of the seven case-control-studies had 30 participants or more and the cross-sectional study of Jenkins et al. (2007) included solely 105 participants (Table. 4.2).

Criteria for in- or exclusion were meagre. Most of the studies defined the requirements regarding diagnostic confirmation of ACL injury only (Beckett et al., 1992; Woodford-Rogers et al., 1994; Smith et al., 1997; Hertel et al., 2004; Jenkins et al., 2007). Loudon et al. (1996) also excluded subjects whose ACL injury occurred beyond two years of testing date, Allen et al. (2000) those who sustained foot trauma in the six months from testing date and Kramer et al. (2007) those subjects with lower extremity surgery or injury within the five months before the testing date.

Foot pain or ankle instabilities could change neuromuscular performance and lead to lower limb kinematics loading the ACL. None of the studies assessed foot pain at the time of injury and only one study recorded previous ankle injury (Kramer, 2007). Surprisingly, it found positive correlation between ankle and ACL injury history as well as positive correlation between visually assessed pes planus and ACL injury history but ND was not significantly different between groups.

In a nutshell, these eight retrospective studies have rather small sample sizes (Table 4.2) and in-/ exclusion criteria are not convincing.

5.2.5 Weak blinding is a strong limitation

Due to the retrospective design of all studies mentioned in Table 4.1, blinding is a main source of bias. Subjects are informed about the purpose of the study and they inevitably know about group affiliation. The assessors can see the scars in case of surgical treatment, they had access to data if they were one of the authors of the paper and no study could prove their ignorance of the study's purpose.

Table 5.4 Blinding and injury mechanisms treated: a comparison between the studies
nc: noncontact, c: contact, ✓: performed, ✓✓: no significant difference (uniform sample or statistical test)

□: results did not support H₁

■: results supported a correlation of ND and ACL injury history

Ref.	Blinding (max. points=10)	Injury mechanisms	Control for injury mechanism
[1]	0	nc:27 c: 23	✓✓
[2]	0	all nc	✓✓
[3]	0	all nc	✓✓
[4]	0	all nc	✓✓
[5]	2	–	–
[6]	0	–	– (mechanism was assessed with questionnaire but evaluation is missing)
[7]	0	–	–
[8]	0	–	–

5.2.6 Comments on the reliability of ND testing

As mentioned in Chapter 2.2.4, intra-tester reliability for ND testing by Brody is good whereas inter-tester reliability is sufficient but not that convincing. A single assessor performed all measurements in most studies (Table 5.5) which increases internal validity but reduces external validity.

As presented in Table 5.5, five studies tested intra-tester reliability again and some also calculated the standard error of measurement (SEM). Since the latter ranged from 0.7 mm to 1.8 mm the conclusions of Hertel et al. (2004) might be questioned. Namely, Hertel et al. (2004) considered 1.6 mm a significant difference between group mean values and did not calculate their SEM.

Strikingly, the healthy controls had mean ND values between approximately 3 and 10 mm. This large range could be due to either low inter-rater reliability of ND testing or a high inter-subject variability of ND in the population.

All studies except the one performed by Allen et al. (2000) modified ND testing by Brody. They measured navicular height during subtalar position in seated position instead of placing the subject in bilateral stance. This procedure is common in clinical practice and easy to perform. But is this variation of ND testing legitimate? Joyce, Arnold and Gansneder (1999) claim that this variation is even more reliable than the testing as described by Brody. ND testing should be improved and standardised.

Table 5.5 ND measurement: reliability, testing position and mean absolute values

ICC: intraclass coefficient, SEM: standard error of measurement, ND: navicular drop, f: female, m: male, ACLi: ACL injured group, ACLni: ACL non-injured group, Ass(1): single assessor

□: results did not support H_1

■: results supported a correlation of ND and ACL injury history

Ref.	Intratester reliability (ICC and SEM)	Position for NH measurement in subtalar neutral position	Mean values for ND (mm)	Approximate absolute difference between groups: ACLi-ACLni (mm)	Information about the assessor
[1]	–	sitting	ACLi: ~12.9mm ACLni: ~6.9mm	5.0	–
[2]	–	sitting	ACLi(m): ~8.4mm ACLi(f): ~5.0mm ACLni(m): ~5.9mm ACLni(f): ~3.0mm	2.5 (m) 2.0 (f)	Ass(1) for each recruitment group (per study period / per gender)
[3]	✓ (0.87)	sitting	<i>Categorisation!! (6-9mm was considered normal)</i>	–	Ass(1), one of the authors (J.K. Loudon)
[4]	✓ (≥ 0.72, SEM: 1.2-1.8mm)	sitting	ACLi: ~6.8mm ACLni: ~6.5mm	0.3	–
[5]	✓ (≥ 0.90, SEM: 1.2mm)	standing (by Brody)	ACLi: ~10.5mm ACLni: ~8.1mm	2.4	Ass(1)
[6]	✓ (≥0.7)	sitting	ACLi: ~8.4mm ACLni: ~6.8mm	1.6	Ass(1), one of the authors
[7]	✓ (0.88, SEM: 0.7mm)	sitting	ACLi: ~10.6mm ACLni: ~10.0mm	0.6	Ass(1) of the authors (W.L. Jenkins)
[8]	–	sitting	ACLi: ~6.3mm ACLni: ~6.5mm	-0.2	Ass(1), with experience

5.2.7 Comments on the validity of ND testing

All studies except the one performed by Allen et al. (2000) marked navicular tuberositas with a skin reference. This method ignores possible measurement bias produced by skin movement. Investigations by Shrader et al. (2005) revealed that palpating the navicular tuberositas in both positions results in significantly higher ND values than comparing the navicular heights based on skin markings. Therefore, Shrader et al. (2005) recommended clinicians to avoid the use of skin markings during ND measurement. To palpate and remark the navicular bone for each navicular height measurement represents a marginal additional effort and stops systematic measurement error. Allen et al. (2000) used an electromechanical device to determine the navicular bone's position in space. It was the only study performing repalpation.

5.2.8 Control for gender differences

Since ND might be a risk factor in one gender only, studies including women and men should check for gender specific effects. As seen in Table 5.6 four studies have used statistical analysis to test for gender specific effects (Beckett, 1992; Allen, 2000; Hertel, 2004; Jenkins, 2007) and three negated a such. Woodford-Rogers et al. (1997) reported stronger association between ND and history of ACL injury in women compared to men but several factors impair these findings: 1) females and males were recruited in different time settings 2) two different assessors performed the measurements in the two study periods 3) male groups were soccer players, whereas female groups consisted of basketball players and gymnasts.

To summarize, females did not show significantly higher ND values neither was the correlation of ND and ACL injury history, if existent, gender specific. Nevertheless, it remains advisable to control for gender as a confounding factor in future research. It is conceivable that females have different demographic characteristics (the influence of foot length is described in Chapter 6.1.1) or different landing strategies (Chapter 4.3.2) which could in turn affect ACL injury risk.

Table 5.6 Gender differences

□: results did not support H₁

■: results supported a correlation of ND and ACL injury history

Ref.	gender	Control for gender specific effects
[1]	females and males	No effects found.
[2]	females and males	In females, absolute ND values were smaller and the association of ND and history of ACL injury was stronger.
[3]	females	–
[4]	females and males	– (not tested!)
[5]	females and males	No effects found.
[6]	females and males	No effects found
[7]	females and males	No effects found
[8]	females	–

5.2.9 Final statement about the methodological quality

As visualised in Table 4.2 the ratings of methodological quality lay between 18 and 26 of maximal 48 points. As they were similar, a weighting with respect to the main hypothesis is not possible.

Rather low ratings are mainly caused by retrospectivity and the lack of blinding. Further potential consists in more accurate definition of the sample population and rigorous sampling procedures. Positive aspects for all studies were the accurate description of methodology, reliable measurements, adherence to methodology and informed consent.

6 Conclusion

6.1 The relevance of ND by Brody

6.1.1 Normative values and interpretation of ND

Nielson et al. (2009) recently found a possible explanation for the large range of normative values of ND. According to the authors, additional foot length of 3 cm entailed an increase of ND of 1.2 mm for males and 0.9 mm for females. Consequently, ND should be normalized to foot length. As none of the studies did so, it is possible that differences in ND were underestimated. Hypothetically, if the control group had greater foot length than the ACL injured group, ND (not normalized) would have been similar in both groups although the normalized ND (static ND /foot length) was only excessive for the ACL injured group. Although it is an adventurous proposition, it is thinkable that differences in ND were underestimated in the study performed by Jenkins et al. (2007). 14 of the 16 subjects in the ACL injured group were women which were reported to have mean heights of 168.2 cm. On the contrary, the majority of the control group were men (50 of 89) and had a mean height of 181.8 cm. This leads to the assumption that the control group had much larger foot lengths and if ND had been normalized to foot length, ACL injured subjects would have shown significantly larger ND values compared to the control group.

Still, two studies (Smith et al., 1997; Kramer et al., 2007) clearly refute association of ND and history of ACL injury. As the control groups were matched for body length and foot length was not considered, argumentation is difficult and doubts persist about the association of ND and history of ACL injury.

6.1.2 ND does not reflect subtalar joint movement during high-impact movements as landing and cutting maneuvers.

So what are the reasons for the conflicting results? Perhaps, ND is not a valid tool to judge foot function but rather reflects passive mobility. Static ND reflects mobility in the ankle complex, mainly in the subtalar joint. Assuming hypermobility in this joint, a dysfunction of stability might develop in case of insufficient muscle control. Such a dysfunction of stability hinders proper force absorption in the foot during drop landings and side cutting maneuvers, continuing in rotation of the tibia and valgisation of the knee.

But hypermobility does not obligatory mean stability dysfunction! Athletes might have the ability to control joint movement during high impact and high velocity tasks. Supposing that pronation can be controlled, a greater range of motion represents a longer way to absorb energy. Assuming perfect muscle control large ND values represent an advantage!

In 2009, Dicharry, Franz, Croce, Wilder, Riley and Kerrigan showed that (static) ND by Brody did not predict dynamic ND measured by three-dimensional motion analysis during walking and running. They assessed static ND measures in 72 healthy subjects. Those were classified into groups: the hypomobile group had mean ND of 8 mm (± 3.8), the neutral group 11.4 mm (± 3.3) and the hypermobile group 18.1 mm (± 5.0). Static ND revealed not appropriate to describe dynamics of the foot, since there were no significant differences in dynamic ND measures between neutral and hypermobile group for walking and running. Dicharry et al. (2009) noted that static ND test overestimated dynamic ND for neutral and hypermobile subjects. They suggested that static ND measurements rather describe mobility of subtalar joint than foot function during walking and running. Apparently, subjects with high static ND values are able to control the range of motion during walking and running. Still, there was some specificity in the hypermobile group: Subjects with high static ND showed significantly higher dynamic ND when comparing running to walking. The authors note that ground reaction forces are several times higher in running compared to walking. It seems reasonable to assume that the muscular control of excessive range of motion in the subtalar joint is more demanding in high-impact maneuvers.

The above study stands out by accurate tracking of dynamic ND during barefoot activity although some limitation must be attributed to skin movement in externally placed markers.

Conversely, earlier studies had confirmed correlation of static ND with characteristics of walking. McPoil and Cornwall (1996) confirmed ND as a predictor of calcaneal eversion during walking, Cavanagh et al. (1997) found that radiographic measures of the medial longitudinal arch correlated with plantar pressure patterns during walking and Nakhaee, Rahimi, Abaee, Rezasoltani and Khademi Kalantari (2007) found moderate correlation between static ND and

maximal force arch index (plantar pressure measurement at maximal ground reaction force).

Non-contact ACL tears typically occur during high-impact movements. But only a few studies investigated whether static ND test reflects foot dynamics during landing and cutting maneuvers. Hargrave, Carcia, Gansneder and Shultz (2003) found comparable peak vertical forces ($F=0.265$, $p=0.769$) and rate of force absorption ($F=0.355$, $p=0.703$) in subjects classified as “supinators” ($ND < 5$ mm), “neutrals” ($ND = 5-10$ mm) and pronators ($ND > 10$ mm). They concluded: “[...] Our findings suggest that factors influencing impact forces in running and landing activities may be entirely different because all subjects in our study made contact with the forefoot first [...]” (p 21)

It is noteworthy to recall a study presented in Chapter 4.3.2 (page 32) in which Mitchell et al. (2008) failed to establish a link between medial plantar loading of the foot during walking and ankle eversion during vertical drop jumps.

Also, healthy subjects classified according to “pronated”, “neutral” and “supinated” foot type ($ND \geq 10$ mm, $ND = 5-9$ mm, $ND \leq 4$ mm) showed similar proprioceptive ability (Cote, Brunet, Gansneder, Shultz, 2005).

Further research is warranted to investigate the relationship between static ND test and dynamic ND during landing and cutting maneuvers. But to date, static ND is not a convincing parameter to quantify dynamic function of the foot. At this point, it has to be mentioned that none of the studies referred to in this argumentation normalized ND to foot length as recommended by Nielson et al. (2009). This could have falsified group classifications.

6.2 The role of dynamic ND during high-impact maneuvers as landing or cutting

For the purpose of research on ACL injury risk factors, motion analysis of the foot has been gross to the present date. With respect to functionality, shoes are kept on and the number of external markers is generally smaller compared with research performed in the podiatric field. Two studies presented in Chapter 4.3.2 at least included foot motion analysis and results favoured that foot pronation plays a role in landing strategies.

Women showed larger foot eversion and knee abduction angles. Whereas static ND could not explain the obvious greater incidence rate in female population, current

literature rather supports gender difference in dynamic foot function. The trend is that females perform landing and cutting maneuvers in a stiffer manner, with smaller knee and hip angles but more knee valgisation and greater force absorption at ankle level (Schmitz, 2007; Decker, 2003; Salci, 2004; McLean, 2004; Pollard, 2010). McLean, Lipfert and van den Bogert (2004) stated that: “[...] increased knee valgus may contribute to ACL injury risk in women, and that the hip and ankle may play an important role in controlling knee valgus during sidestepping [...]” (p 1008) A more recent study by Norcross, Blackburn, Goerger and Padua (2010) suggests that subjects with greater energy absorption at the ankle during the first 100 ms from a double-leg jump landing, show significantly higher anterior tibial shear forces ($r=0.525$, $p=0.005$). Subtalar joint movement was not inquired, but assuming a forefoot landing strategy in plantar flexion of the talocrural joint and unblocked position of the subtalar joint in slight supination, pronation is probably involved in energy absorption. Possibly, greater energy absorption at the ankle leads to hyperpronation, which then leads to increased anterior tibial translation.

It is essential to further research on the role of foot kinematics in force absorption during landing and cutting maneuvers.

6.3 Causal relationship of ND and non-contact ACL injury

Correlation and association are not able to make a causal statement! If subtalar pronation correlates with tibial internal rotation or tibial anterior translation during tasks, it is essential whether power flows from proximal to distal extremity or vice versa. Does the foot follow tibial movement or is subtalar pronation the cause of tibial internal rotation? Bellchamber and van den Bogert (2000) publicated a study addressing this question. Three-dimensional motion analysis and force plate data in ten male and ten female subjects were collected during walking and running. Figure 6.1 illustrates the correlation of pronation and tibial internal rotation in runnen. Figure 6.2 refers to the power flow. During walking, power flow occurred from proximal to distal. In running, periods of positive power flow, indicating the foot leading the tibia, were observed between 35% - 80% of total stance phase. Inter-subject variability in running was rather high as 25% had abnormal power flow patterns.

No equivalent studies were found for high-impact tasks as landing or cutting maneuvers.

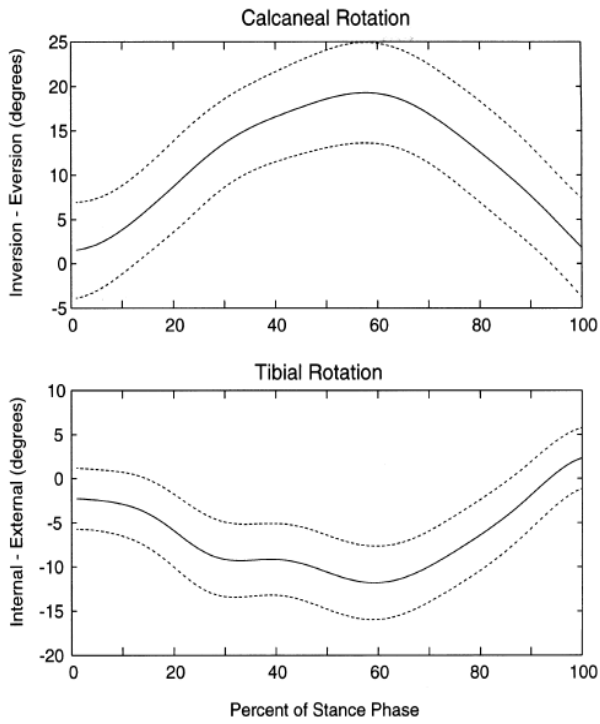


Figure 6.1 Average calcaneal in-/ eversion and tibial ex-/ internal rotation during running. Calcaneal eversion correlates with tibial internal rotation in running.

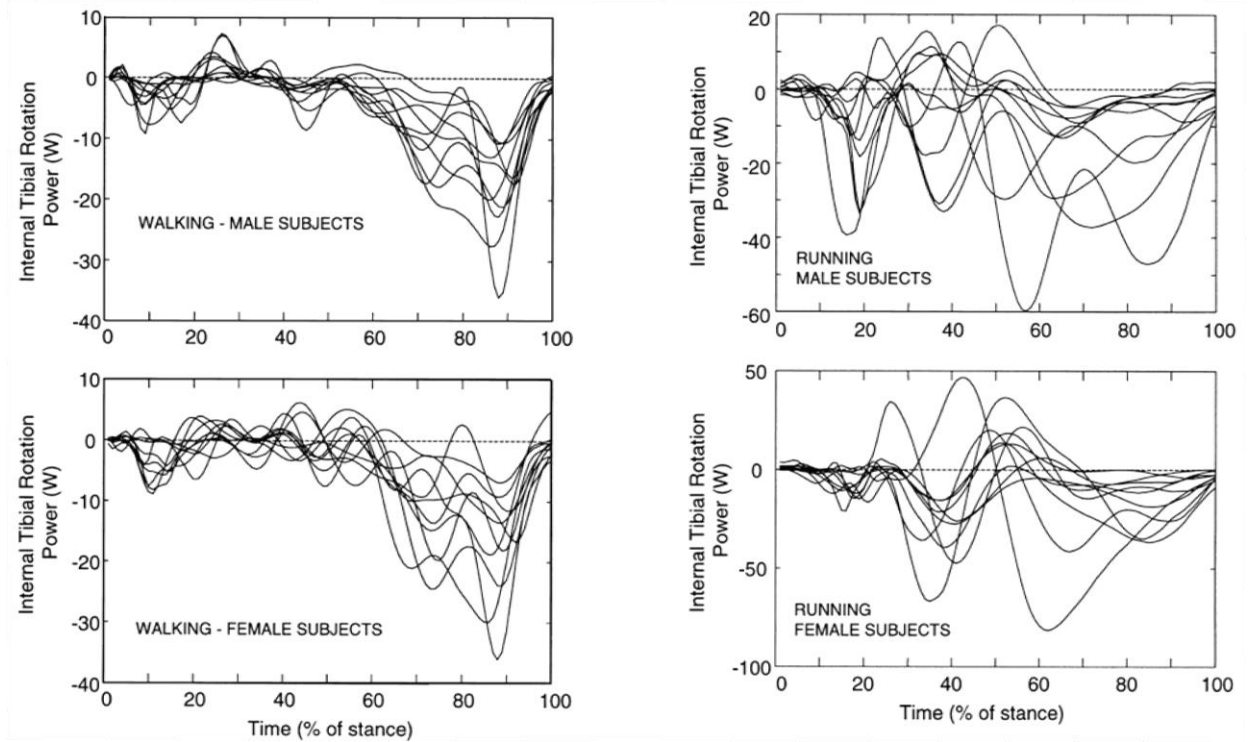


Figure 6.2 Average power curves during walking (on the left) and running (on the right) for each subject. Positive power indicates distal control of the tibia (tibia follows foot motion).

6.4 Future directions for research

Further research is needed to improve the understanding of foot function during high-impact maneuvers that put athletes at risk as well as to make a definite statement about static and dynamic ND as risk factors for ACL injury in post-adolescent athletes. The following Table presents questions to be answered and important methodological requirements deduced from this literature review.

Table 6.1 Future directions for research

Unanswered questions	Methodological requirements
Is excessive static ND a risk factor for ACL injury and is it an efficient screening factor for athletes at risk?	<ul style="list-style-type: none"> - Repalpate the navicular bone in weight-bearing position instead of using skin markings - Normalize ND values with foot length - Use prospective study designs to compare athletes who sustained ACL injury during a season with those who did not
What is the role of dynamic ND (pronation in the subtalar joint) during landing and cutting tasks in healthy subjects?	<ul style="list-style-type: none"> - Motion (video) analysis of healthy subjects during landing and cutting maneuvers - Perform maneuvers barefoot - Use adequate marker sets to track motion in the subtalar joint as it is done in the podiatric field
Is excessive dynamic ND a risk factor for ACL injury and is it an efficient screening factor for athletes at risk?	<ul style="list-style-type: none"> - Motion (video) analysis of healthy subjects during landing and cutting maneuvers - Perform maneuvers barefoot - Use adequate marker sets to track motion in the subtalar joint as it is done in the podiatric field. - Use prospective study designs to compare athletes who sustained ACL injury during a season with those who didn't
Does normalized static ND measured by repalpation of the navicular bone in weight-bearing position correlate with dynamic ND measured by motion (video) analysis during landing and cutting maneuvers?	<ul style="list-style-type: none"> - Cross-sectional study with large sample (several hundred participants) in the population at risk
Is it possible for a physical therapist to detect excessive subtalar joint pronation during landing and cutting maneuvers with the naked eye?	
Are prevention programs which explicitly focus on the integration of foot function more efficient than conventional ones?	

7 Practical applications

7.1 Screening for athletes at risk

ND alone is not a sufficient screening method to detect subjects at risk. Static ND test quantifies subtalar joint mobility and is not able to reflect dynamic ND during high-impact tasks such as landing or cutting maneuvers. Those are related to ACL injuries and should be focussed on. Unfortunately, visual assessment of dynamic ND is very difficult. Even if sport-specific high-impact maneuvers were performed barefoot, the displacement is difficult to assess visually because it ranges from 3 to 13 mm only. Three-dimensional motion analysis is not practicable for broad applications because of expensive material and time consumption. Nevertheless, subjects should be asked for previous ankle injuries and pain in the foot. Those symptoms indicate a lack of muscular control at foot level and if combined with excessive static ND could likely represent increased risk to sustain ACL injury. While most of the studies on risk factors of ACL injury have been retrospective, Hewett et al. (2005) performed a prospective study and identified knee valgisation during drop jumps as a predictor of ACL injury. Assuming a subject with excessive valgus collapse, it seems essential to me to detect the dominant neuromuscular deficiency. Possible hypothesis are:

- Insufficient muscle control of the foot muscles controlling foot pronation and sustaining the medial longitudinal arch
- Insufficient muscle control of the hip's abductors and external rotators
- Insufficient abdominal stability

7.2 Prevention programs

It is sensible to integrate current findings in prevention programs. Good results were achieved in some studies which included plyometric training, agility training and education about leg alignment during sport-specific tasks (Mandelbaum et al., 2005; Olsen et al, 2005)¹³. All of them are mainly closed chain exercises and therefore are affected by foot structure and function. The author thinks that the neuromuscular control of the ankle complex is often trained unconsciously and is convinced that consciously training proprioception and neuromuscular control of the foot complex during sports-specific tasks can further improve prevention programs. Ideas for practical

¹³ Chapter 8.2 : List of effective ACL preventative Programs published by Bush B.M. (2010)

implementations are listed in Table 7.1 and some examples of exercises are documented in the appendix (Chapter 8.3).

Prevention programs should use sport-specific exercises and consciously consider foot function by integrating closed-chain exercises, strengthening foot muscles (especially those absorbing ground reaction forces) and improving foot proprioception and foot-knee coordination. Finally, leg alignment must be automatized because athletes are most at risk in dual task or reactive situations (Chan, Huang, Chang, Kernozek, 2009; Sell et al., 2006; McLean et al., 2004).

Table 7.1 Suggestions for the implementation of ACL injury prevention programs (without prioritisation)

Interventions and practical examples

-
- a. Education of athletes about optimal lower extremity alignment during landing and cutting maneuvers

 - b. Agility training during sport-specific high-impact maneuvers that put athletes at risk for ACL injury. E.g. landing and cutting maneuvers (Chapter 8.3, exercises (2))

 - c. Stability training with unstable bases (Chapter 8.3, exercises (5))

 - d. Somatosensory training by performing some training sequences barefoot or outdoor on unlevelled ground (small paths in the forest, vita-parcours, slanting terrain, in high grass)

 - e. Plyometric training as quick hops (flat, upward, forward, lateral), scissors jumps or hurdle race (Chapter 12.3., exercises (1))

 - f. Self-exercises for regeneration of foot and calf muscles and improvement of somatosensory information provided by the foot. (E.g. Chapter 8.4)

 - g. Training of strength and springiness in the lower extremity focussing on foot function. E.g. sprint up- and downstairs, cutting and jumping tasks on an inclined terrain.

 - h. Coordination training aiming at controlling the flattening of the medial longitudinal arch. E.g. FBL¹⁴ exercises such as “Gewölbebauer”, “Platzieren”, “Geisha-Gang”, “Pinguin”, “Federball” (Eicke-Wieser, 2006)
-

¹⁴ „Funktionelle Bewegungslehre“ (german) or „functional kinematics“ is a therapy concept developed by Klein-Vogelbach S. (1909-1996)

7.3 Restriction of hyperpronation by orthotics is contraindicated in some cases

The discussion about foot orthotic prescription is controversial. Some important arguments are given in Table 7.2. Summing up, I would like to say that generalised prescription of foot orthoses is not recommended. For some individuals foot orthoses proved successful for pain reduction although exact causality is unknown. Foot orthoses should not be used only to enhance proprioceptive control because the selective locking of joint movement potentially puts subjects at risk for acute and chronic injuries. Clinical assessment of the entire lower extremity is essential to interpret foot function because hyperpronation may represent a “normal” adaptation to abnormalities.

Table 7.2 Arguments in the discussion of foot orthotics

Pro-arguments	Contra-arguments
Foot orthoses reduce ACL injury rate (Jenkins et al., 2008, mentioned in Chapter 6.2)	As power flow during walking occurs from proximal to distal, orthoses interrupt force absorption strategy and load the knee (Bellchamber and van den Bogert, 2000). We do not know the power flow during landing or cutting maneuvers yet.
Foot orthoses stabilize rearfoot movement and reduce internal rotation of the knee (Hadley et al., 1999; Rome and Brown, 2003; Jenkins et al., 2009)	Positive effects of foot orthoses are not based on the control of subtalar joint and subsequently, knee joint motion. Instead, foot orthoses enhance proprioceptive control and this effect is only valid for slow movements such as single-leg squat or lateral step down. (Hertel, Sloss and Earl, 2005; Cote et al., 2005).
Foot orthoses reduce peak vertical ground reaction forces in walking, running, landing.	Foot orthoses include a broad range of construction materials and ways of manufacture. In contrast to over-the-counter wedges, custom-made orthoses are individualised. Different types of orthoses show different, sometimes opposite effects. (Mündermann, Nigg, Humble and Stefanyshyn, 2002).
Foot orthoses reduce pain in foot and knee joint (e.g. McLean, Davis, Hamill, 2008)	Hyperpronation can be a compensation for structural abnormalities of the lower extremity. Tiberio (1988) described that foot abnormalities like forefoot varus and rearfoot varus are compensated by excessive pronation in order to establish ground contact required for propulsion during gait. Gross (1995) stated that crus varum was compensated by excessive subtalar pronation so that the medial foot properly touches the ground. This effect is shown in Figure 8.3.

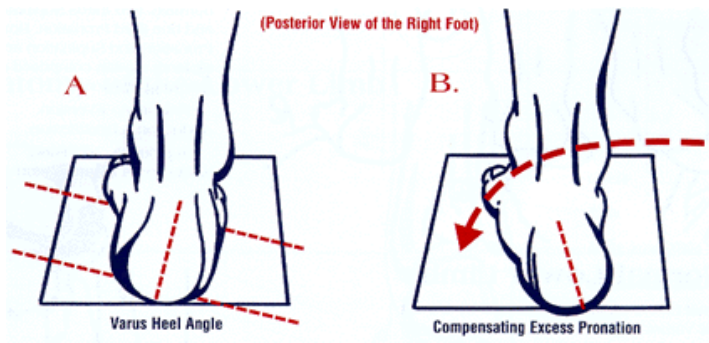


Figure 7.1 Excessive pronation (B) compensates for structural abnormalities like crura varum (A)

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List of abbreviations

ND	navicular drop
ACL	anterior cruciate ligament
lig.	ligament
m /mm.	musculus /musculi

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Author's declaration

Herewith, I certify that I authored this literature review independently, with no help of other parties and using the references given.

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8 Appendix

8.1 Methodological evaluation

8.1.1 Rating scale and glossary¹⁵

0 points	not sufficient / no information available
1 point	just sufficient
2 points	satisfactory

Citations are presented in *italic*.

confounding factor	A variable which is not the one you are interested in but which may affect the results of trial.
odds ratios	A ratio of events to non-events. If the event rate for a disease is 0.2, its non-event rate is 0.8 and therefore its odds are 2/8
CI	The confidence intervals range around a study's result within which we would expect the true value to lie. CIs account for the sampling error between the study population and the wider population the study is supposed to represent
p-value	The probability that a particular result would have happened by chance.
ANOVA	Generalisation of t-tests to more than two groups /to more than two variables.
F	For single-factor ANOVA the statistical test compares F-value of sample population to the F-distribution (for number of participants -1, degrees of freedom -1). Significant difference is deduced if empiric F-value ist greater than critical F-value.
X ²	Pearson's Chi-square test compares X ² -value of sample population to the X ² -distribution (degrees of freedom -1). The calculation includes relative frequency in the sample and compares it to expected relative frequencies under the null-hypothesis. This statistical test allows ordinal parameters. Requirements: the variables must be mutually exclusive!
R ²	Quantifies to what extent a prediction can account for the observed variance in the sample population. It gives a statement about quality of the model (association).
r	Measures the strength of a linear correlation. Values range from -1 to 1. 0 means there is no correlation at all.
SD	Standard deviation
ICC	Intraclass correlation coefficient (descriptive statistical test)
SEM	Standard error of the mean

¹⁵ Sources:

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8.1.2 Criteria and specifications

1.1 Hypothesis clearly stated	
1.2 Hypothesis clearly answered	
2 Sample	
2.1 sample population defined	2 points: clearly stated; 1 points: inferable
2.2 recruitment	2 points: random; 1 point: convenience sample; 0 points: sampling method not described, not structured, low responder rates
2.3 sample size justified	2 points: power calculation performed; 1 points: subject number per group ≥ 30
2.4 entry criteria and exclusions stated and justified	examples for entry criteria: clinical diagnosis of ACL tear, sport, activity level, injury mechanism (non-contact), treatment procedures (surgical or conservative), time past since ACL-tear; examples for exclusion: present pain in lower extremity, history of foot injury or foot pain, foot orthotics.
2.5 control group matched or randomised	minimal matching accounts for age, gender, height and weight
2.6 control group is comparable to sample (table 1)	2 points: table 1 complete, p-values; 1 point: relevant variables presented in the text; 0 points: groups are not comparable (lack of transparency or insufficient matching)
3 Data collection and data processing	
3.1 accurate description of data collection	
3.2 accurate description of statistical analysis	
3.3 reliability and validity of measurements	ND as described by Brody is assumed to have good intra-tester and inter-tester reliability and to be a valid indicator of hyperpronation. (mentioned in Chapter 2.2.4.) 2 points: ND test performed as described by Brody and intra-tester reliability analysis undertaken; 1 point: slight variation of ND test by Brody, missing reliability analysis.
3.4 reproducibility of results / primary results presented in a table	
3.5 adherence to methodology	
3.6 missing data	technical problems, use of incomplete data sets should be avoided or at least documented
3.7 informed consent	
4 Blinding	
4.1 subjects ignore purpose	for example when data sets are used post-hoc
4.2 subjects ignore group membership	for example when data sets are used post-hoc
4.3 assessors ignore purpose	for example when data sets are used post-hoc
4.4 assessors are independent	
4.5 assessors ignore group membership	
5 statistical analysis	
5.1 alpha level	2 points: 5% or 1%
5.2 presentation of statistical results is complete and comprehensible	
5.3 control of confounding factors / discussion of limiting factors	examples: exclusion of confounding factors like side differences in ND or differences in foot length, accounting for co-variables by multiple correlation models or data normalization, cautious interpretation of results, emphasizing of limiting factors.
6 external validity	The appropriateness by which results can be applied to non-study patients or populations.

8.1.3 [1] Beckett et al. (1992)

1.1	Hypothesis clearly stated		The purpose of this study was to determine if a relationship exists between hyperpronation and ACL injuries.
1.2	Hypothesis clearly answered		The ACL injured group subjects had greater navicular drop test than non-injured subjects.
2	Sample		
2.1	sample population defined		
2.2	recruitment		
2.3	sample size justified		50 per group
2.4	entry criteria and exclusions stated and justified		ACL injured group: arthroscopic examination of ACL rupture and corresponding written diagnosis from orthopedic surgeon; control: no history of lower extremity pathology.
2.5	control group matched or randomised		Random sample (...), composed of patients and clinical staff members.
2.6	control group is comparable to sample (table 1)		Table 1* is missing; descriptions reveal that ACL injured subject had greater weight.
3	Data collection and data processing		
3.1	accurate description of data collection		questionnaire (medical history, mechanism of injury, diagnosis) and bilateral ND test
3.2	accurate description of statistical analysis		two-factor mixed model analysis of variance (ANOVA) with side and group as factors; t-test for differences in gender and mechanism of injury (contact vs non-contact)
3.3	reliability and validity of measurements		ND test variation: sitting starting position; no testing for reliability performed
3.4	reproducibility of results / primary results presented in a table		incomplete (gender differences? p-values?)
3.5	adherence to methodology		
3.6	missing data		
3.7	informed consent		
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets		
4.2	subjects ignore group affiliation		
4.3	assessors ignore purpose /post-hoc use of data sets		
4.4	assessors are independent		
4.5	assessors ignore group affiliation		
5	statistical analysis		
5.1	alpha level		p=0.01
5.2	presentation of statistical results is complete and comprehensible		no significant difference between between sides: F(1.196)=0.13, p=0.72; significant difference in ND between injured subjects and controls: F(1.196)=129.6, p=0.01
5.3	control of confounding factors / discussion of limiting factors		Did the authors evaluate and interpret the information of the questionnaires?
6	external validity		lacking information about subject recruitment, setting of data collection, qualification and experience of assessor(s)
Quality evaluation (maximum 48 points)		18	

*		ACL injured	controls	p-value
	gender	11 f / 39 m	18 f / 32 m	
	age (yr)	22.9 +-7.6	21.8 +-9.4	
	height (cm)	177.8 +- 10.3	173.7 +-9	
	weight (kg)	79.8 +- 17.3	67.6 +- 12.4	

8.1.4 [2] Woodford-Rogers et al. (1994)

1.1	Hypothesis clearly stated	green	The purpose of our study were to 1) determine if clinical measurements used to assess pronation and anterior translation of the tibia on the femur discriminate between ACL injured and ACL non-injured athletes matched for sport, team and position and to 2) identify those measures which are the strongest discriminators between the two groups.
1.2	Hypothesis clearly answered	green	Discriminant analysis of the data from the football players indicated that navicular drop, anterior drawer with 20lb of force, and maximum manual drawer were the best predictors of group classification. Same for females.
2	Sample		
2.1	sample population defined	yellow	high school and college athletes. Sports not determined.
2.2	recruitment	red	Sampling happend in two phases during a two year period and appears rather unsystematik (convenient). In the first phase, only males (football players) were selected, and in the second only females (basketball players and gymnasts).
2.3	sample size justified		
2.4	entry criteria and exclusions stated and justified	yellow	ACL injury must be unilateral and confirmed arthroscopically or during arthrotomy. BUT: no specificity of injury mechanism, activity level, time since injury etc. (Some subjects were not yet allowed to stand in weight-bearing because of recent surgery. Nevertheless, they were included because measurements were taken from the non-injured leg.) For subjects in the controll group, no history of a knee injury more severe than a first degree sprain was required.
2.5	control group matched or randomised	green	matched for sport, position, playing time, gender, body length and weight in both sampling phases.
2.6	control group is comparable to sample (table 1)	yellow	table 1* missing
3	Data collection and data processing		
3.1	accurate description of data collection	green	
3.2	accurate description of statistical analysis	green	
3.3	reliability and validity of measurements	yellow	ND test variation: comparing navicular distance to the ground in sitting position and single-leg stance; no testing for reliability preformed
3.4	reproducibility of results / primary results presented in a table	green	
3.5	adherence to methodology	yellow	In men both legs where assessed. Since the majority did not show a difference between righth and left, data was averaged. In women, only the uninjured leg was measured.
3.6	missing data	green	
3.7	informed consent	green	
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets	red	
4.2	subjects ignore group affiliation	red	
4.3	assessors ignore purpose /post-hoc use of data sets	red	
4.4	assessors are independent	red	single assessor per recruitment group (two different assessors for whole data set)
4.5	assessors ignore group affiliation	red	
5	statistical analysis		
5.1	alpha level	green	p=0.01 and p=0.05
5.2	presentation of statistical results is complete and comprehensible	yellow	no significant differences between sides for ND: F(1.13)=0.67, p=0.43; discriminant analysis: 87.5% of females were correctly classified using ND and anterior drawer of the knee. For males the equivalent value was 71.5%. For all subjects, group classification was successful in 70%. regression analysis: 60% of variance between groups explained by ND and anterior drawer tests in females. But only 22% for male football players.
5.3	control of confounding factors / discussion of limiting factors	yellow	potential other risk factors mentioned: intercondylar notch width, playing surface, footwear, body weight, fitness level, general athletic ability. The authors further note: "We also made the assumption, based upon the analysis of the measures obtained bilaterally (...), that the uninjured lower extremity of ACL-injured athletes is representative of the injuredl imb prior to injury."
6	external validity	red	lacking information about subject recruitment, setting of data collection, qualification and experience of assessors
	Quality evaluation (maximum 48 points)		25

*			
high school and college football players	ACL injured	controls	p-value
gender	14 m	14m	
age (yr)	19.1 +- 6	18.1 +- 1.6	
height (lb)	211 +- 47.9	199.6 +- 36.6	
weight (in)	73.3 +- 3.3	72.3 +- 2.9	
female basketball players (2) and gymnasts (6)	ACL injured	controls	p-value
gender	8 f	8 f	
age (yr)	19.5 +- 1.7	19 +- 1.2	
height (lb)	128 +- 17	126.9 +- 12.8	
weight (in)	64.6 +- 3.7	63.3 +- 2.6	

8.1.5 [3] Loudon et al (1996)

1.1	Hypothesis clearly stated		The purpose of this study was to examine the correlation between static postural faults in female athletes and the prevalence of noncontact ACL injury. (standing pelvic position, femoral anteversion, standing sagittal and frontal knee position, hamstring length, prone subtalar joint position and navicular drop test). A static posture, consisting of anterior pelvic tilt, anteverted hips, tight hamstrings, genu recurvatum, and subtalar joint pronation may place an individual in knee hyperextension and increased internal tibial rotation during dynamic movement, putting greater stress on the ACL (figure 2).
1.2	Hypothesis clearly answered		Results indicate that excessive sagittal knee position (Hyperextension), excessive ND, and excessive subtalar joint pronation (rearfoot position in non-weight-bearing position) were predictors of group classification. All other variables did not significantly contribute to determination of group membership. The combination of knee hyperextension with excessive subtalar joint pronation proved to be a strong discriminator between injured and noninjured groups.
2	Sample		
2.1	sample population defined		female athletes participating in a sport (basketball, volleyball, tennis, soccer) two to three times a week
2.2	recruitment		not described
2.3	sample size justified		
2.4	entry criteria and exclusions stated and justified		arthroscopic examination of the ACL rupture and injury occurrence within two years of testing date, unilateral ACL tear, 8 surgical and 12 nonoperative treatments
2.5	control group matched or randomised		matched for age, gender, height, weight, activity level
2.6	control group is comparable to sample (table 1)		
3	Data collection and data processing		
3.1	accurate description of data collection		pelvis tilt by Kendall et al., femoral anteversion by Ruwe et al., hamstring length in supine position and knee neutral position, maximal knee extension in standing position, Q-angle method by Magee, navicular drop comparing sitting with subtalar neutral position and standing with relaxed foot, rearfoot position in prone position and subtalar neutral
3.2	accurate description of statistical analysis		pre-measurement categorisation of values in normal, low and high range based on existing literature; McNemar test of symmetry between normal and abnormal categories with alpha-level = 0.05; Chi-square values presented in table 4; multivariate analysis to assess combination of variables in discriminating between groups; conditional step-wise logistic regression to assess for multivariate significance; alpha-level = 0.05 (results showed in table 5)
3.3	reliability and validity of measurements		Intratester reliability (cohen's kappa) was assessed for each variable by the test-retest method on 10 lower limbs. For ND the kappa value was 0.87.
3.4	reproducibility of results / primary results presented in a table		Categorisation blurs the results!
3.5	adherence to methodology		Low and high range categories were summarised because many variables were only represented in two groups.
3.6	missing data		
3.7	informed consent		
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets		
4.2	subjects ignore group affiliation		
4.3	assessors ignore purpose /post-hoc use of data sets		One of the authors performed all measurements.
4.4	assessors are independent		
4.5	assessors ignore group affiliation		
5	statistical analysis		
5.1	alpha level		p=0.05
5.2	presentation of statistical results is complete and comprehensible		univariate analysis: Chi-square values for ND 7.14, p=0.008; multivariate analysis: Chi-square values for ND 8.73, p=0.003
5.3	control of confounding factors / discussion of limiting factors		
6	external validity		lacking information about subject recruitment and setting of data collection.
Quality evaluation (maximum 48 points)		26	

8.1.6 [4] Smith et al. (1997)

1.1	Hypothesis clearly stated		The purpose of this study was to examine the relationship between hyperpronation and the occurrence of noncontact injury to ACL.
1.2	Hypothesis clearly answered		Hyperpronation as measured by the ND test was not a predictor of ACL injury, and, thus, may not be a predisposing factor to noncontact ACL injuries.
2	Sample		
2.1	sample population defined		female athletes
2.2	recruitment		
2.3	sample size justified		
2.4	entry criteria and exclusions stated and justified		ACL injury mechanism is non-contact, partial or complete ACL tear asserted by MRI or arthroscopy. (Two of 14 subjects had bilateral ACL injuries. Two of the 16 knees were treated conservatively.)
2.5	control group matched or randomised		matched for gender, age, height and weight
2.6	control group is comparable to sample (table 1)		table 1* missing
3	Data collection and data processing		
3.1	accurate description of data collection		ND test by Brody; calcaneal stance position test.
3.2	accurate description of statistical analysis		No difference was found between sides, hence the means were used for statistical evaluation. Only unilateral ACL-injured subjects were compared to control group (12 subjects respectively). Regression analysis of ND values to predict group adherence.
3.3	reliability and validity of measurements		ND test variation: sitting starting position; intratester reliability was assessed on ND test by requiring the control group to perform the tests twice for each foot. ICCs were 0.72 (SEM=0.179mm) for the left foot and 0.82 (SEM=1.15) for the right foot.
3.4	reproducibility of results / primary results presented in a table		tables 1 and 2
3.5	adherence to methodology		
3.6	missing data		
3.7	informed consent		
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets		
4.2	subjects ignore group affiliation		
4.3	assessors ignore purpose /post-hoc use of data sets		
4.4	assessors are independent		
4.5	assessors ignore group affiliation		
5	statistical analysis		
5.1	alpha level		p=0.05
5.2	presentation of statistical results is complete and comprehensible		only reliability analysis: 0.72 and 0.82 ICC for ND test on left and right side respectively
5.3	control of confounding factors / discussion of limiting factors		Authors explain that the different results to Beckett (1992) are related to difference in sample (more females, smaller height, smaller ND values in general, smaller sample, exclusively non-contact injury mechanism). Calcaneal stance values differed between right and left sides. Hence, the were not entered in statistical analysis. In contrast to Woodford the groups were not matched for team, position, participation level. Like all retrospective studies, this study is based on the assumption that the uninjured leg is representative of the preinjury state.
6	external validity		lacking information about subject recruitment, setting of data collection, qualification and experience of assessor(s)
Quality evaluation (maximum 48 points)		23	

*		ACL injured	controls	p-value
	gender	7 f / 7 m	8 f / 7 m	
	age (yr)	21.7 +- 0.83	21.14 +- 2.03	
	height (cm)	174.81 +- 8.29	177.35 +- 11.31	
	weight (kg)	72.32 +- 13.47	72.99 +- 14.81	

8.1.7 [5] Allen M.K., Glasoe W.M. (2000)

1.1	Hypothesis clearly stated		The null hypothesis was that navicular drop would not differ between groups (subjects with a history of ACL tears, noninjured matched controls).
1.2	Hypothesis clearly answered		The independent t-test showed a statistically ($p > 0.05$) larger ND in the ACL group.
2	Sample		
2.1	sample population defined		
2.2	recruitment		
2.3	sample size justified		
2.4	entry criteria and exclusions stated and justified		no history of foot or ankle trauma during the six months before testing, ACL tear confirmed either by MRI or clinically by examination and KT-1000 testing performed by a physician. (16 subjects had undergone reconstructive surgery, and two had been treated conservatively.)
2.5	control group matched or randomised		matched by gender, age and limb.
2.6	control group is comparable to sample (table 1)		table* missing, data incomplete
3	Data collection and data processing		
3.1	accurate description of data collection		Metrecom (FARO Medical Technologies Inc, Lake Mary, FL) measurement described.
3.2	accurate description of statistical analysis		Measurements on each foot was performed twice to test reliability. The average of the ACL-injured limb was then entered in statistical analysis. Independent t test was used to assess difference in ND between groups.
3.3	reliability and validity of measurements		Positions for ND test same as described by Brody. Intratester reliability of ND measurements: 0.9 ICC (SEM: 1.19mm)
3.4	reproducibility of results / primary results presented in a table		primary results presented in tables 1, 2 and 3
3.5	adherence to methodology		
3.6	missing data		
3.7	informed consent		
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets		
4.2	subjects ignore group affiliation		
4.3	assessors ignore purpose /post-hoc use of data sets		The metrecom measures the 2 positional points in 3-dimensional space and calculates the change in distance for the investigator, who is blinded from the results during the test. A single examiner performed measurements.
4.4	assessors are independent		
4.5	assessors ignore group affiliation		
5	statistical analysis		
5.1	alpha level		$p = 0.05$
5.2	presentation of statistical results is complete and comprehensible		t-tests: $p < 0.05$ comparing ACL injured group (both injured and non-injured limb) to the control group
5.3	control of confounding factors / discussion of limiting factors		Skin movement over bony navicular and neglect of medial and anterior directed movement of the bone elicit important bias. This should be eliminated by the use of the metrecom. The examiner continuously controlled subtalar neutral in non-weight-bearing position by palpation of the talus. ND values of females and males revealed to be comparable (rebutting Loudon's argument that ND was smaller because his sample included more females).
6	external validity		lacking information about subject recruitment, setting of data collection, qualification and experience of assessor.
Quality evaluation (maximum 48 points)		26	

*		ACL injured	controls	p-value
	gender	6 f / 12 m		
	age (yr)	29.9 +- 9.5	29.9 +- 8.6	
	height (cm)			
	weight (kg)			

8.1.8 [6] Hertel et al. (2004)

1.1	Hypothesis clearly stated		We hypothesized that increased ND, increased q-angle, negative leg length discrepancy, increased hip rotation ROM and greater anterior pelvic tilt will be significantly associated with having a history of ACL injury.
1.2	Hypothesis clearly answered		Increased ND and anterior pelvic tilt, regardless of gender, are significantly associated with a history of ACL tear. For Q-angle, leg length and hip rotational ROM the hypothesis was refuted.
2	Sample		
2.1	sample population defined		
2.2	recruitment		people responding to flyer distributed on large university campus. No information about responder rates.
2.3	sample size justified		
2.4	entry criteria and exclusions stated and justified		Control group had no history of ACL injury to either limb. (Four of 20 subjects, all women, had bilateral ACL tears, all ACL injuries occurred during sport participation between 3 months and 7 years before measurements, all subjects had received surgical reconstruction.)
2.5	control group matched or randomised		matched for gender, age, height and weight.
2.6	control group is comparable to sample (table 1)		table 1* missing
3	Data collection and data processing		
3.1	accurate description of data collection		questionnaire to assess injury mechanism and time of injury; ND test by Brody, Q-angle lying supine, two different measurements of leg length lying supine, active hip rotation ROM lying prone, pelvic tilt by Krawiec et al.
3.2	accurate description of statistical analysis		Each limb was treated as individual subject. Multifactorial ANOVAs for each variable comparing injured and control group, gender and limb (involved or not). Stepwise logistic regression analyses comparing injured limbs and side-matched control limbs. Second stepwise logistic regression analysis with only those variable which were significantly associated with ACL injury. Classification of limbs into three classes (lowest, middle and highest third) based on measurements was undertaken in order to calculate odds ratios and their 95% CI.
3.3	reliability and validity of measurements		ND test variation: sitting starting position; The examiner practiced each measurement technique during pilot testing until test-retest reliability analysis revealed ICC greater than 0.7
3.4	reproducibility of results / primary results presented in a table		table 1
3.5	adherence to methodology		
3.6	missing data		
3.7	informed consent		
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets		
4.2	subjects ignore group affiliation		
4.3	assessors ignore purpose /post-hoc use of data sets		examiner was one of the authors of the study.
4.4	assessors are independent		
4.5	assessors ignore group affiliation		
5	statistical analysis		
5.1	alpha level		p=0.05
5.2	presentation of statistical results is complete and comprehensible		initial regression analysis: for ND $r^2=0.14$ (p=0.004); second regression analysis including ND and pelvic tilt: $r^2=0.42$ (p=0.001); The highest category of ND values (ND>8mm) had a 20 times higher risk to sustain ACL injury compared with the lowest (ND<6.3mm). ND and anterior pelvic tilt correctly predicted ACL injury history of 73% of injured limbs and 76% of uninjured limbs. ND and anterior pelvic tilt explained 42% of variance associated with ACL injury history.
5.3	control of confounding factors / discussion of limiting factors		mentioned limitations include: small sample size, differences in ND and pelvic tilt are potential post-traumatic or post-surgical adaptations and not predisposing factors for ACL rupture, ND and anterior pelvic tilt only partly explained the variance associated with ACL injury history, therefore other factors must be considered.
6	external validity		Population was not chosen systematically, sample was small.
Quality evaluation (maximum 48 points)		26	

*	ACL injured	controls	p-value
gender	10 f / 10 m	11 f / 10 m	
age (yr)	20.7 +- 1.4	20.4 +- 1.3	
height (cm)	175 +- 9	173 +- 9	
weight (kg)	72.5+- 17.7	72.2+- 12.2	

8.1.9 [7] Jenkins et al (2007)

1.1	Hypothesis clearly stated		The purpose of this study was to determine whether a relationship exists between foot structure and ACL injury in female and male athletes who participate in soccer and basketball.
1.2	Hypothesis clearly answered		Values derived from subtalar joint neutral position measurement and the navicular drop test were not associated with ACL injury in collegiate female and male soccer and basketball players.
2	Sample		
2.1	sample population defined		soccer and basketball athletes (what age, what activity level, what context?)
2.2	recruitment		recruitment in sports teams of one university (105 athletes).
2.3	sample size justified		
2.4	entry criteria and exclusions stated and justified		ACL-injured group: 16 subjects had a history of ACL injury and subsequent ACL reconstruction surgery. No consideration of time of surgery, injury mechanism, sport level, foot injuries. Control group: 89 subjects had no history of knee injury
2.5	control group matched or randomised		The overall sample of 105 subjects is comparable for age and consists of similar numbers of females and males. Activity level was not considered. Due to recruitment strategy, ACL injured and non-injured group are not matched for gender, height and weight.
2.6	control group is comparable to sample (table 1)		table 1 allows comparison between gender which shows that men have greater mean height and weight. No comparison between ACL injured and control group for age, height, weight, activity level possible. (87.5% of the ACL injured group is female)
3	Data collection and data processing		
3.1	accurate description of data collection		bilateral measurements of ND and subtalar joint neutral position, calculation of mean values for each subjects.
3.2	accurate description of statistical analysis		A paired t-test was used to investigate significant differences in ND between injured and uninjured side in ACL injured group and between the right and left side in the control group; independent t-test was used to determine correlations between ND and group membership, and ND and gender. X ² analysis was used to find correlations between ACL injury and sports. Relative risk: injured subjects divided by uninjured subjects. Attributable risk: percentage of uninjured subjects minus percentage of injured subjects.
3.3	reliability and validity of measurements		ND test variation: sitting starting position; Intratester reliability analysis was performed for the primary investigator measuring ND of ten uninjured subjects. ICC for ND was 0.88 (SEM: 0.7mm).
3.4	reproducibility of results / primary results presented in a table		tables 2, 3 and 4
3.5	adherence to methodology		
3.6	missing data		
3.7	informed consent		
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets		
4.2	subjects ignore group affiliation		
4.3	assessors ignore purpose /post-hoc use of data sets		
4.4	assessors are independent		
4.5	assessors ignore group affiliation		ACL status was reported via an other subject. Nevertheless, the assessor being W.L. Jenkins itself had access to the data and scars were not covered.
5	statistical analysis		
5.1	alpha level		p=0.05
5.2	presentation of statistical results is complete and comprehensible		paired t-test: p=0.720 and p=0.770 for difference between sides in ACL injured and control group respectively. independent t-test: p=0.88 for difference in ND between groups and p=0.43 between gender. X ² : soccer players have a 1.6fold risk sustaining ACL injury compared to basketball players.
5.3	control of confounding factors / discussion of limiting factors		Differences in ND between sides, between ACL injured limb and non-injured limb, between gender and differences between sports could be excluded (post-hoc) by statistical testing.
6	external validity		Subjects were recruited on a single university. Results in other settings might be different. Insufficient information about activity level also impedes the transfer in other settings.
Quality evaluation (maximum 48 points)		24	

8.1.10 [8] Kramer et al. (2007)

1.1	Hypothesis clearly stated		Our primary purpose was to examine lower extremity skeletal alignment, flexibility patterns, generalized laxity, postural control, and previous ankle sprain history in females with and without a history of ACL injury (...). Secondary purpose was to scrutinize the relationship between ankle sprain history and ACL history.
1.2	Hypothesis clearly answered		ACL injury history was found to be significantly related to increased generalized laxity, greater genu recurvatum, less iliotibial band flexibility. This study also provides initial evidence that a kinetic chain relationship may exist between ankle sprain and risk of ACL injury. Preliminary analysis comparing groups found no significant differences for ND.
2	Sample		
2.1	sample population defined		physically active females
2.2	recruitment		no information available.
2.3	sample size justified		
2.4	entry criteria and exclusions stated and justified		ACL injured subjects were cleared to participate fully in exercise and sports, ACL injuries occurred within 5 years of study start. All subjects did not have lower extremity injury or surgery in the 5 months prior to testing. Controls did not have any history of ACL injury.
2.5	control group matched or randomised		matched for gender, age, height, weight.
2.6	control group is comparable to sample (table 1)		table 1* missing.
3	Data collection and data processing		
3.1	accurate description of data collection		survey about knee and ankle injury history. 16 lower extremity measures bilaterally (Beighton laxity scale, visually determined foot type, Morton's toe, ND, pelvic tilt, leg length, tibial varum, standing Q-angle, genu recurvatum in standing position, femoral anteversion).
3.2	accurate description of statistical analysis		preliminary analysis of continuous variables between groups, categorization of measurement of each limb in thirds (ND ≤5mm, ND=6-7, ND ≤8), Chi-square test to identify associations between categories and ACL history group status, identification of significant variables, which were then entered into series of discriminant analyses in order to find the most strongly associated factors. Additionally, discriminant analysis was performed for history of ankle sprain (instead of ACL injury).
3.3	reliability and validity of measurements		ND test variation: sitting starting position; (Vernier caliper, marking midpoint of the navicular bone). No testing for reliability performed.
3.4	reproducibility of results / primary results presented in a table		tables 2, 4, 5. Unfortunately, categories are presented only for those variables significant in preliminary analysis. It would be interesting to know whether, ND was significantly correlating with ACL injury when categorized. Notice, that visual assessment of foot type is in some way such a categorization and it was found to be significantly correlated with history of ACL injury.
3.5	adherence to methodology		
3.6	missing data		
3.7	informed consent		
4	Blinding		
4.1	subjects ignore purpose /post-hoc use of data sets		
4.2	subjects ignore group affiliation		
4.3	assessors ignore purpose /post-hoc use of data sets		
4.4	assessors are independent		
4.5	assessors ignore group affiliation		assessor was not informed about ACL status, but surgical scars were visible and could be interpreted by the experienced assessor.
5	statistical analysis		
5.1	alpha level		p=0.05
5.2	presentation of statistical results is complete and comprehensible		preliminary analysis: p=0.01 for Beighton laxity scale, tibial varum, Q-angle, pelvic tilt, 90/90 test (ischio-crural flexibility test), Ober's test; $\chi^2=5.93$, p=0.02 for ankle sprain history; $\chi^2=6.36$, p=0.04 for foot type (pes planus) discriminant analysis: 21% of variance between groups could be explained by generalized laxity, genu recurvatum and decreased iliotibial band flexibility.
5.3	control of confounding factors / discussion of limiting factors		some measurements might be the result of post-injury or post-surgical adaptations due to the retrospective design.
6	external validity		sample was rather small in size and fairly homogenous consisting only of young adult females. Insufficient information about activity level also impedes the transfer in other settings.
Quality evaluation (maximum 48 points)		24	

*	ACL injured	controls	p-value
age (years)	21 ± 2.1	19.6 ± 1.3	
height (cm)	168.9 ± 8.3	167 ± 6.8	
weight (kg)	66.4 ± 9.3	62.5 ± 5	

8.1.11 Comparison of relevant information

Ref.	sample size	Number of subjects with bilateral ACL injury	Sports	Control for sports differences	groups are comparable for activity level	mean ages and SD für ACLi and ACLni group	intratester reliability tested (ICC)	blinding (max. 10 points)	Normalization of ND with foot length	Was the measurement of ND in subtalar neutral assessed in sitting or standing position?	plausible values for ND (means and SD)?	approximate difference in mean values for ND between groups (ACLi-ACLni)
[1]	ACLi: 50 ACLni: 50	0	-	-	-	ACLi: 22.9 ±7.6 ACLni: 21.8±9.4	-	0	-	sitting	ACLi: -12.9mm ACLni: -6.9mm	5.0
[2]	ACLi: 22 ACLni: 22	0	soccer (m), basketball (f), gymnasts (f)	matched control groups	√	ACLi: 19.1 ±6 ACLni: 18.1 ±1.6	-	0	-	sitting	ACLi(m): -8.4mm ACLi(f): -5.0mm ACLni(m): -5.9mm ACLni(f): -3.0mm	2.5 (m) 2.0 (f)
[3]	ACLi: 20 ACLni: 20	0	soccer, basketball, volleyball, tennis	-	√	ACLi: 26.5 ±7.6 ACLni: 26.2 ±7.8	√ (0.87)	0	-	sitting	<i>Categorisation!! (6-9mm was considered normal)</i>	-
[4]	ACLi: 12 (2 further had bilateral ACL tears and were excluded) ACLni: 12	0 (2)	-	-	-	ACLi: 21.7 ±0.8 ACLni: 21.1 ±2.0	√ (≥ 0.72, SEM: 1.2-1.8mm)	0	-	sitting	ACLi: -6.8mm ACLni: -6.5mm	0.3
[5]	ACLi: 18 ACLni: 18	0	-	-	-	ACLi: 29.9 ±9.5 ACLni: 29.9 ±8.6	√ (≥ 0.90, SEM: 1.2mm)	2	-	standing (by Brody)	ACLi: -10.5mm ACLni: -8.1mm	2.4
[6]	ACLi: 20 ACLni: 20	4	-	-	-	ACLi: 20.7 ±1.4 ACLni: 20.4 ±1.3	√ (≥0.7)	0	-	sitting	ACLi: -8.4mm ACLni: -6.8mm	1.6
[7]	ACLi: 16 ACLni: 89	0	soccer, basketball	√√	- (same university is not considered sufficient)	all were between 17 and 24 years old.	√ (0.88, SEM: 0.7mm)	0	-	sitting	ACLi: -10.6mm ACLni: -10.0mm	0.6
[8]	ACLi: 33 ACLni: 33	6	-	-	-	ACLi: 21 ±2.1 ACLni: 19.6 ±1.3	-	0	-	sitting	ACLi: -6.3mm ACLni: -6.5mm	-0.2

Ref.	categorisation of outcome variables	post injury treatment	injury mechanism	control for injury mechanism (√√: no differences found)	control for side differences in the control group (√√: no differences found)	control for side differences in ACL- injured group (√√: no differences found)	ND measurement in ACL injured group	gender	check for gender specific effects	information about assessor	external validity
[1]	-	-	nc: 27 c: 23	√√	√√	√√	both limbs separately	females and males	none	-	-
[2]	-	-	all nc	√	√√	-	uninvolved limb	females and males	In females, absolute ND values were smaller and the association of ND and history of ACL injury was stronger.	single assessor per recruitment group (per study period / per gender)	-
[3]	√ (for all statistical evaluation)	surgical: 8 conservative: 12	all nc	√	-	-	involved limb	females	- only female subjects in this study	single assessor, one of the authors (J.K. Loudon)	-
[4]	-	surgical: 14 conservative: 2	all nc	√	√√	√√	both limbs separately	females and males	- equal numbers of females and males in both groups	-	-
[5]	-	surgical: 16 conservative: 2	-	-	√√	√√	both limbs separately	females and males	none. ND values for females (10.2mm) and males (10.7mm) were comparable.	single assessor	-
[6]	√ (not for descriptive statistics, but for regression model and odds ratio)	all surgical	-	- (mechanism reported but not evaluated)	- (both limbs measured but no evaluation presented)	- (both limbs measured but no evaluation presented)	involved limb	females and males	none.	single assessor, one of the authors	-
[7]	-	all surgical	-	-	√√	√√	mean values from both legs	females and males	none.	single assessor, one of the authors (W.L. Jenkins)	-
[8]	√ (not for preliminary statistics, but for discriminant analysis)	all surgical	-	-	-	-	involved limb	females	- only female subjects in this study	single assessor, with experience	-

8.2 List of effective ACL preventative programs (Bush B.M., 2010, pages 55/6)

Author	Sport	Number tested	Duration	Sex	Random	Equipment	Strength training	Flexability Training	Agility Training	Flexability Training
Griffis et al (1989)	Basketball	not reported, 2 teams	8 years	Female	No	Jump Box, Balance	No	No	Yes	No
Caraffa et al (1999)	Basketball, volleyball, soccer	T, 300 C, 300	3 seasons	Male	No, prospective	Balance Boards	Proprioceptive, neuromuscular, facilitation exercises	Yes	No	Yes
Hewett et al (1999)	Basketball, volleyball, soccer	1263	1 year	Male/Female	Yes	Jump Box, balance	Yes	No	No	No
Mykleburst et al (2003)	Team Handball	900	3 years	Female	No	Wobble Board, balance foam mats	No	Yes	Planting neuromuscular control	Yes
Gilchrist et al (2004)	Soccer	561	1 year	Female	Yes	Cones, Soccer ball	Yes, gluteus medius abduction, extension, hamstrings, core	yes	Deceleration, sport specific	yes
Mandelbaum et al (2005)	Soccer	T, 1041 C, 844	2 years	Female	No, voluntary enrollment	Cones, soccer ball	Hamstrings, core	Yes	Soccer specific with decel.technique	Yes
Olsen et al (2005)	Team Handball	1837 1	1 year	Male/Female	Yes, cluster randomized controlled trial	Wobble board; balance foam mats	Yes	Yes	Cut, neuromuscular control	Yes

Agility Training	Plyometrics	Author	Proprioception	Programs Strengths	Programs Weakness	Outcome
Yes	Landing Technoque	Griffis et al (1989)	Deceleration Pattern, (3-step shuffle)	Changing Deceleration and landing techniques	not randomized, unpublished	89% decrease in noncontact ACL injury
No	No	Caraffa et al (1999)	Yes, Balance Board activities	Mechanoreceptor/ proprioceptive training	additional equipt.. Not effective on large scale	87% decr. In NC ACL, injury rate reduced to 0.15/1000
No	Yes	Hewett et al (1999)	Yes	Decr. Peak landing forces, decr. Valgus and varus perturbation, incr.	One-to One program in sports facility; not feasible to implement across large cohort	14 ACLs reported; female injury rates 0.43 untrained vs. 0.12 trained vs. male control 0.9 over 6 week program; untrained group 3.6-4.8 higher injury rates of ACL injury
Planting neuromuscular control	Landing Technique	Mykleburst et al (2003)	Balance activities on mats and boards	Compliance to programs monitored, instructional video	Not Randomized	In elite division, risk of injury was reduced ampoong those who completed program, 53.8% and 61.5% reduction of ACL injury
Deceleration, sport specific	landign technique, multiplanar	Gilchrist et al (2004)	Strength onfield perturbation on grass	Instructional video web site, compliance monitored	1 year interventions, began on day 1 of season	Overall 72% reduction of ACL injury, 100% redc. In preactive NC and contact ACL in last 6 weeks of season
Soccer specific with decel. techniqe	landing technique an: multiplanar	Mandelbaum et al (2005)	strength onfield perturbation on grass	Instructional Video, Web site; compliance monitored	not randomized; inherent selection bias	injury rates year 1, 88% reduction in NC ACL; year 2, 74% reduction in NC ACL
Cut, neuromuscular control	Landing technique	Olsen et al (2005)	Balance activity on mats and boards	Randomized; compliance monitored, reduction of injury	Efficacious component(s) of intervention not known	129 acute knee and ankle injuries overall; 81 in control (0.9 overall, 0.3 training, 5.3 match) versus 48 injuries in intervention (0.5 overall, 0.2 training, 2.5 match) 80% reduction in ACL

8.3 Suggestions of interventions in a ACL injury prevention program

(1a) two-legged plyometric jumps



Level 1:

Quick jumps on the spot, emphasizing dorsal extension of the ankle joint during the jump in order to land in a slightly pre-stretched position of the Achilles tendon. This aims at enhancing explosive plantarflexion-contraction. The movement should be similar to a elastic spring.

Level 2:

Every fifth jump must be a jump upward on the first step and back

Level 3:

two-legged jumps upstairs

Level 4:

Two-legged jumps downstairs

Repetition numbers: ca 10 jumps

Sets: 3

Speed: fast. Time of ground contact should be as short as possible

Pause: active regeneration (e.g. 3 minutes of easy jogging)

(1b) single-legged plyometric jumps



1. Single-leg jumps going upstairs (ca. 10 steps).
2. Going down the stairs normally in easy jogging pace
3. Single-leg jumps going upstairs with the other leg
4. Same as 2.

Repetition numbers: 3

Sets: 3

Speed: fast. Time of ground contact should be as short as possible.

Pause: active regeneration (e.g. 3 minutes of easy jogging)



(2a) Two-legged vertical jump landing with external focus (rings)

1. Two-legged vertical jump in order to touch one of the rings
2. Two-legged landing on a the 9 cm thick gymnastic mat

Repetition numbers and sets should be determined based on the qualitative performance possible.

Repetition number: 5-10

Sets: ca. 3

Speed: irrelevant

Pause: active regeneration (e.g. 5 minutes of shot training which focussed on the upper extremity)



(2b) Single-leg landing with external focus (rings)

1. Two-legged vertical jump in order to touch one of the rings
2. Single-leg landing on a the 9 cm thick gymnastic mat
3. Exercise both legs and reflect, which side has better coordinative performance and which is more susceptible to ACL injury.



(2c) Reactive single-leg landing

1. Two-legged vertical jump
2. Another subject standing in front signals by a hand movement, which leg should be used for landing
3. Reactive single-leg landing on a the 9 cm thick gymnastic mat with the appropriate leg.



(2d) jumping and landing with dualtask

1. Two-legged vertical jump over an obstacle holding a ball
2. Pass the ball during the jump
3. Two-legged landing on a ca. 25 cm mat
4. Jump on one leg and keep balance



(3) Parcours in minimal time possible

1. Touch the wall with one hand (start)
2. Cross the mats stepping on different mats with each leg
3. Perform a long jump from the first to the second circle
4. Perform side-cutting maneuvers into the circles three, four and five
5. Finish with an exact two-legged jump in the tire without getting caught.
6. Run back
7. re-do steps 1-6
8. re-do steps 1-6
9. Touch the wall (stop)

Sets: 3-5

Speed: maximal

Pause: active regeneration



(4) running upstairs for jumping power

1. Head start of 3 to 5 steps
2. Take 3-4 steps at once to run upstairs
3. Go down carefully, slowly, but still taking 2 steps at once
4. Re-do 1. to 3. five times

Sets: 3

Speed: maximal going upstairs, slow when going down

Pause: full regeneration by pause of 3 to 5 minutes.

Comment: The advantage of the stairs is that overcoming height requires power and exactly hitting the steps requires precise movement. Hence this exercise trains strength and coordination. It can be seen as a preparative exercise for landing tasks because it trains concentric force and is less demanding than eccentric activities.



(5) unstable bases to improve proprioception and to train leg alignment

Repetition numbers and sets or duration of the exercise should be determined based on the qualitative performance. Athletes should max out the exercise level but as long as the leg alignment can be hold.

(5a) standing on a gymnastic ball

(5b) squats on a gymnastic ball



(5c) mat and wobble board exercise proposed by Olsen et al. (2005)



8.4 “10 steps for a healthy foot”

1. Massage the intertarsal muscles from proximal to distal.



2. Gently flex and extend your toes.



3. Form a transversal arch with your forefoot.



4. Fix the transversal arch with your right hand and move the first metatarsal bone downwards.



5. a) Try to hold the twisted (antipronated) position of your foot.

b) Place the heel and ball of your foot on the ground and keep your foot medially hollow.



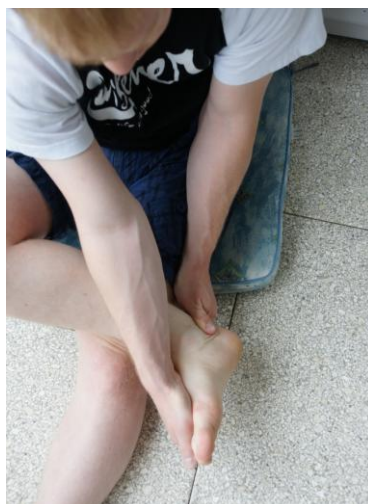
6. Massage the ventral muscles of your shank by intermittent pressure with the fingers of your left hand. The other hand stabilizes the knee.



7. Station your leg in a relaxed position as seen below and massage the medial part of your calf (kneading movement).



8. Run your thumb and forefinger along the achilles tendon.



9. Change body position as shown below and massage the lateral part of your calf (kneading movement).



10. Fix your ankle in a neutral position (left hand) and use your fist (right hand) to stimulate the sole of your foot.

