Sannamari Lepojärvi

NORMAL VARIATION OF THE TIBIOTALAR JOINT IN DYNAMIC COMPUTED TOMOGRAPHY
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Abstract

The normal tibiotalar joint is a stable structure, where only a minor widening of the ankle mortise and rotation of the fibula is caused by normal flexion-extension movements and joint loading. The most common injury mechanism is excessive external rotation of the ankle, which may induce an ankle fracture or an injury of the syndesmosis ligaments, leading to instability of the joint. Subsequent surgical fixation can cause malreduction and dysfunction of the joint by restricting normal motion, which may lead to altered tibiotalar joint loading conditions and cause long-term complications, such as osteoarthritis. In order to correctly evaluate the potential post-traumatic conditions, clinicians must know the normal movements of the fibula in the distal tibiofibular joint and the talus in the upper ankle joint under weight-bearing conditions. Until now, the normal dynamics of the syndesmosis and upper ankle joint, as well as the changes in rotations have been unknown, and the aim was to answer these questions.

In the first study, the distal tibiofibular syndesmosis was assessed on non-weight-bearing computed tomography (NWBCT) scans in order to provide standardized measures of the syndesmosis in cross-sectional imaging. Second, a distal tibiofibular syndesmosis was investigated in upright weight-bearing CT (WBCT) scans in the neutral standing position and under maximal internal and external rotational stress. Third, the normal anatomy and rotational dynamics of the upper ankle joint was observed.

The first study demonstrated that in axial CT imaging of the syndesmosis, the location of the fibula was either anteriorly or centrally in the tibial incisura in 88–97% of patients in both the supine position with resting ankles, and in the neutral standing position. If the fibula lies posteriorly, malreduction should be considered.

The second study demonstrated that when the ankle is maximally rotated, the fibula slides back and forth in the tibial incisura with 1.5 mm total movement and a rotation of 3°, but the distal tibiofibular joint is not widened. In internal rotation of the ankle, the talus is rotated externally, the fibula moves, and the fibula moves to the posterior part of the tibial incisura in 40% of subjects. In external rotation of the ankle, the talus is rotated internally, and the fibula moves concomitantly slightly anteriorly. The results of the third study show that the talus rotates in the ankle mortise 10°, with no change in the medial clear space (MCS) and no significant lateral widening in the joint space.

Minimal intrasubject variation (less than 1 mm at all measurement points) was observed in the total rotational range of motion, while in some measurements the intersubject variation was large in both supine, neutral standing, and rotational stress images. Sex or age did not affect most of the measurements; only in maximal external rotation was a minor tilting of the talus seen in the older population.

These findings suggest that the contralateral ankle can and probably should be used as a reference when possible malreduction of the syndesmosis or tibiotalar ankle joint instability is suspected.

Keywords: ankle, inferior tibiofibular joint, rotational dynamics, syndesmosis, tibiotalar joint, upper ankle joint, WBCT

Ensimmäinen tutkimus osoitti, että normaali nivelle sijaitsee alavalla pohjeluun yläosaan tai nivelen keskellä 88–97 %:lla tutkituista potilaista. Jos taas pohjeluu on siirtynyt nivelen takaoastaan, tulee epäselvän virheasennon.

Toisen tutkimuksen tulokset osoittivat, että kiertyorasituksissa pohjeluu liikkuu syndesmoosialueella 1.5 mm ja kiertyy 3 astetta, mutta nivel ei levene sivuaan sisään takaoastaan. Telaluu sisäkierrorossa nivel on liikkuu 40 %:lla tutkituista vapaaehtoisista koehenkilöistä syndesmoosialueen takaoastaan, ja ulkokierrorossa nivel on liikkuu 60 %:lla tutkituista vapaaehtoisista koehenkilöistä syndesmoosialueen takaoastaan. Kolmas tutkimus osoitti, että telaluu kiertyy maksimaalisen ulko- ja sisäkierron välillä 10 astetta ilman merkittävää mediaalisen tai lateraalisen nivelraon leviämistä. Kaikissa tutkimuksissa todettiin, että mikäli koehenkilöitä verraataan keskenään, samojen mitatsaukon väliset erot ovat merkittäviä. Mikäli taas verraataan saman koehenkilön molempia nilkkojia keskenään, mitatsaukissa ei ole merkittävää puolieroa. Ainoa mittaustulos, joka jäätti toistaiseksi koehenkilöissä olisi 10 astetta ilman merkittävää mediaalisen tai lateraalisen nivelraon leviämistä.

Tutkimusten perusteella todetaan, että potilaan terveltä normaaliattutokonemogrammatuotoksista syntyvät erilaiset ja niitä mittaamattomia mittaustuloksia aina potilaan henkinen tai liikkaaminen aiheuttavat. Tutkimusten perusteella todetaan, että potilaan terveltä normaaliattutokonemogrammatuotoksista syntyvät erilaiset ja niitä mittaamattomia mittaustuloksia aina potilaan henkinen tai liikkaaminen aiheuttavat.
Sampalle, Eemelille ja Maijalle
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Sannamari Lepojärvi
List of abbreviations and definitions

AW    anterior width  
AWTFS anterior width of the distal tibiofibular syndesmosis  
AWTTJ anterior width of the tibiotalar joint  
AITFL anterior inferior tibiofibular ligament  
ATFL  anterior talofibular ligament  
CBCT  cone-beam computed tomography  
CFL   calcaneofibular ligament  
CT    computed tomography  
CI    confidence interval  
CTDI  computed tomography dose index  
DI    depth of the tibial incisura  
ER    external rotation  
ICC   intraclass correlation coefficient  
IOL   intraosseal ligament  
LI    length of the tibial incisura  
MCS   medial clear space  
MMT   medial malleolar tangent line  
MSCT  multislice computed tomography  
MRI   magnetic resonance imaging  
NI    narrowest part of the tibial incisura  
NWBCT non-weight-bearing computed tomography  
ORIF  open reduction internal fixation  
PA    pronation-abduction  
PE    pronation-external rotation  
PITFL posterior inferior tibiofibular ligament  
PTFL  posterior talofibular ligament  
PW    posterior width  
PWTFS posterior width of the distal tibiofibular syndesmosis  
PWTIJ posterior width of the tibiotalar joint  
ROF   rotation of the fibula  
ROT   rotation of the talus  
SA    supination-adduction  
SE    standard error  
SER   supination-external rotation  
ST    sagittal translation of the fibula
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<td>TFCS</td>
<td>tibiofibular clear space</td>
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<td>TFO</td>
<td>tibiofibular overlap</td>
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<tr>
<td>TyT</td>
<td>translation of the talus</td>
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<tr>
<td>US</td>
<td>ultrasonography</td>
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<tr>
<td>WBCT</td>
<td>weightbearing computed tomography</td>
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List of original publications

This thesis is based on the following publications, which are referred to throughout the text by their Roman numerals:


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1 Introduction

Ankle injuries are common among both the general population and at all levels of athletic participation. Of all ankle injuries, 85% are sprains, and 85% of those are lateral inversion sprains (Balduini & Tetzlaff 1982, Doherty et al. 2014, Hootman et al. 2007). Ankle fracture occurs in approximately 15% of inversion injuries (Clanton & Porter 1997, Jensen et al. 1998, Michelson 1995, Thordarson 1996). The injuries vary greatly in severity and degree.


Pathological movement of the talus is commonly detected from the lateral translation of the talus in the ankle mortise, i.e., medial clear space (MCS) widening, though unstable movement is also rotational. Lateral translation is important to detect; just one millimeter of lateralization significantly reduces the contact area and peak forces in axial loading and may cause osteoarthritis (Harris & Fallat 2004, Lloyd et al. 2006, Ogilvie-Harris et al. 1994, Ramsey & Hamilton 1976). Biomechanical studies suggest that if the MCS width is five millimeters or more, a total rupture of the deep deltoid ligament is probable, and operative treatment is indicated (McConnell et al. 2004, Michelson et al. 2007, Park et al. 2006). Increased external rotation of the talus is hard to detect because it does not always cause lateral translation of the talus on radiographs (Donken et al. 2013). The failure to diagnose increased talar rotation might explain, to some extent, the

Until recently, computed tomography (CT) of the extremities has only been feasible in the supine position, while the lower extremities normally function in the upright position. Previous studies of the dynamics of the ankle have been cadaveric or biomechanic, leaving a lot of potentially important information of the internal derangements of the joint and possible loading changes in obscurity. In order to correctly evaluate possible instability or malreduction after injury or surgery, the information of the normal anatomy as well as the normal movements of the fibula and talus under normal loading and rotational stress should be known. Since the new weightbearing cone-beam CT (WBCT) allows this kind of imaging for the first time, the aim was to find the answers to these questions.
2 Review of the literature

2.1 Anatomy of the syndesmosis and upper ankle joint

The upper ankle joint, or tibiotalar joint, is comprised of the distal tibiofibular syndesmosis and the tibiotalar joint, which work together to allow coordinated movement of the rearfoot.

2.1.1 Distal tibiofibular joint

The distal tibiofibular joint (or tibiofibular syndesmosis) is between the convex medial surface of the distal fibula and the concave notch of the distal tibia. The opposed surfaces form proximally a fibrous joint and distally the cartilage-covered mortise joint for the talus (Elgafy et al. 2010, Hermans et al. 2010, Hocker & Pachucki 1989, Jenkinson et al. 2005, Katznelson et al. 1983, Kennedy et al. 2013, Sora et al. 2004). The interosseous ligament and membrane complex unite the tibia and fibula, and the joint is strengthened in the front and in the behind by anteroinferior and posteroinferior tibiofibular ligaments (AITFL and PITFL, respectively), which together resist the axial, rotational, and translational forces trying to separate the bones. The AITFL runs from the anterior tubercle of the tibia to the anterior tubercle of the fibula, an average of 5 mm above the articular surface from the proximal-medial to the distal-lateral direction. It also cross-

2.1.2 Tibiotalar joint

The tibiotalar joint is formed by the lateral malleolus of the fibula, the medial malleolus of the tibia and the talus. The stability of the joint is enhanced by the shape of the bones, since the dome-shaped talus fits tightly into the concave undersurface of the tibia (Arndt et al. 2004, Lundberg et al. 1989, Stormont et al. 1985, Tochigi et al. 2006). The anatomic shape of the talus has some individual variation, which may affect the function of the joint and joint loading conditions. For example, patients with adult-acquired flatfoot deformity tend to have more valgus in their talus anatomy compared to controls (Cody et al. 2016).

The tibiotalar joint is stabilized by several ligaments, including the anterior talofibular ligament (ATFL), the posterior talofibular ligament (PTFL), the calcaneofibular ligament (CFL), and the deltoid ligament complex. The ATFL, PTFL, and CFL support the lateral aspect of the ankle, while the deltoid ligament provides medial support (Arndt et al. 2004, Attarian et al. 1985a, Attarian et al. 1985b, Beumer et al. 2003, Burks & Morgan 1994, Campbell et al. 2014). On the dorsolateral aspect of the ankle is the ATFL, which courses from the lateral malleolus toward the talus in an anteromedial direction. It prevents the anterior displacement, excessive inversion, and internal rotation of the talus. The CFL courses from the lateral malleolus inferiorly to the lateral aspect of the calcaneus and restricts excessive supination of both the tibiotalar and subtalar joints. The PTFL runs posteriorly from the lateral malleolus to the posterolateral aspect of the talus

Fig. 2. Tibiotalar joint ligamentous anatomy. (ATFL: anterior talofibular ligament; CF: calcaneofibular ligament; PTFL posterior talofibular ligament.)

On the medial side of the ankle, anatomic descriptions are not as straightforward. The deltoid ligament has both superficial and deep layers. It consists of several ligamentous bands, which can be difficult to differentiate. The medial ligament complex is a multifascicular structure, originating from the medial malleolus and spreading out to the talus, calcaneus, and navicular bone. The most constant parts of the deltoid ligament complex are the deep posterior tibiotalar ligament, and superficially, the tibionavicular and tibiospring ligaments. The most important band is the deep posterior tibiotalar ligament, which is the largest; it is the primary source of medial stability of the ankle. It resists valgus angulation, posterior translation, and lateral displacement of the talus. The superficial layer takes part in stabilizing more distally the calcaneonavicular complex and also resists exter-

2.2 Biomechanics of the ankle


The kinematics are based on the geometry of the articular surfaces and the anatomic relationship of the bony structures, especially the tibial plafond to the talus. The shape of the tibiotalar joint allows torque to be transmitted from the lower leg (internal and external rotation) to the foot (pronation and supination) during weight bearing (Kleipool & Blankevoort 2010, Stormont et al. 1985). Since the anterior portion of the talus is more broadly shaped, it fills the mortise more completely during dorsiflexion. This maximizes the contact between the articular surfaces and improves stability. It also causes the decrease in stability during plantarflexion and makes the ankle more vulnerable to ligamentous injuries in plantarflexion (Kleipool & Blankevoort 2010, Miller & Skalak 2014, Stormont et al. 1985). The three-dimensional movement of the ankle is a result of the asymmetric shape of the talus and the elastic fixation of the syndesmosis, allowing the movement between the fibula and tibia (Wang et al. 2015). The primary motions are often defined as occurring in three cardinal planes: sagittal (plantar flexion-dorsiflexion), frontal (inversion-eversion), and transverse (internal rotation-external rotation). Motions are not isolated due to oblique axes of rotation (e.g., supination is a combined movement of adduction, inversion, and flexion) (Kleipool & Blankevoort 2010, Leardini et al. 1999, Wang et al. 2015).

2.2.1 Biomechanics of the syndesmosis

Both the form of the bony structures and the contribution of the ligaments to tibiotalar joint stability are crucial. In a syndesmosis, the ATITFL is the first to resist forces that cause the external rotation of the fibula (Bartonicek 2003, Beumer et al. 2003, Beumer et al. 2006, Dattani et al. 2008, Xenos et al. 1995), and thus...
it is prone to damage in excessive supination external rotation (SER) injuries. In anatomical specimens, the AITFL was also the most important stabilizer of the syndesmosis compared to other individual syndesmotic ligaments (Ogilvie-Harris et al. 1994, Beumer et al. 2006).

Normal gait causes only minimal widening and fibular rotation in an intact syndesmosis, but if the ankle is rotated externally, some posterior translation of the fibula is allowed (Beumer et al. 2006, Close 1956, Fujii et al. 2010, Katznelson et al. 1983, Ogilvie-Harris et al. 1994, Sarsam & Hughes 1988, Teramoto et al. 2008, Xenos et al. 1995). Also, in experimental studies, the external rotation of the ankle resulted in the largest and most consistent displacements of the fibula relative to the tibia at the level of the syndesmosis (Beumer et al. 2006). If the AITFL were cut, a medial traction force would increase the diastasis at the level of the syndesmosis from 1.1 to 2.0 mm. Talar tilt angles would also increase from 10° to 15° (Teramoto et al. 2008).

### 2.2.2 Biomechanics of the tibiotalar joint

According to clinical and biomechanical studies, primary stabilizers of the ankle are the medial malleolus and the posterior deep deltoid ligament. They prevent lateral shift of the talus and limit dorsiflexion of the ankle or anterior rotation of the leg when the foot is planted. The posterior part of the deep deltoid ligament also resists internal rotation of the talus (Boss & Hintermann 2002, Campbell et al. 2014, Hintermann et al. 2004, Michelson et al. 1992, Michelson et al. 2002, Pettrone et al. 1983, Phillips et al. 1985, Rasmussen & Kromann-Andersen 1983, Sasse et al. 1999). Ex vivo kinematic studies also show that the ATFL prevents both excessive inversion, internal rotation, and anterior displacement of the talus from the mortise, and the strain is increased while the ankle moves from dorsiflexion into plantarflexion (Bahr et al. 1998, Fujii et al. 2010, Kobayashi et al. 2013, McCullough & Burge 1980, Rasmussen & Kromann-Andersen 1983, Sasse et al. 1999, Stormont et al. 1985). The ATFL is a primary restraint in inversion and has a lower maximal load and energy values as compared with the PTFL, CFL, AITFL, and deltoid ligament complex. This may explain why the ATFL is the most frequently injured of the lateral ligaments (Attarian et al. 1985a, Bahr et al. 1998, Fujii et al. 2010, Holmer et al. 1994).

As previously mentioned, normal gait causes only minor talar rotation and pronation during dorsal/plantar flexion of the ankle, and only minimal widening and fibular rotation in an intact syndesmosis (Beumer et al. 2006, Fujii et al. 2010).

In biomechanical cadaver studies, if the tibia was rotated internally 20° and externally 10°, the talar rotational range of motion was 5–6°. In a radiostereometric analysis of patients, Beumer et al. (2003) reported that in ankles with reconstructed lateral ligaments, the talus translates on average to 16° externally, 1.9 mm anteriorly, and 3 mm laterally during an external rotation moment of 7.5 Nm in the supine position. After drop-landing the motion in the tibiotalar joint is dorsiflexion with a minor rotation (12°;SD7° dorsiflexion, 2°;SD2° eversion, and 3°;SD2° internal rotation) (Fukano et al. 2014).

Patients with functional instability of the ankle demonstrated altered subtalar rotation in ankle dorsiflexion, but no statistical differences in plantar flexion were detected in either the tibiotalar or subtalar joints between the functionally instable ankle and the contralateral healthy joints (Kobayashi et al. 2013).

2.3 Ankle fractures and syndesmosis injuries

2.3.1 Epidemiology and classification

Ankle fractures represent approximately 10% of all fractures, with incidences of rotational ankle fractures ranging from 71–187 per 100,000 per year (Jensen et al. 1998, Thur et al. 2012). They are among the most frequently surgically treated fractures (Schepers 2012) and vary from stable lateral malleolus fractures to open fracture dislocations. Ankle fractures can be caused by direct axial loading (e.g., tibial pilon fractures), or indirect trauma, as in rotational ankle fractures. Both of these distinct entities involve the same joint but have substantially different treatments and prognoses.

Rotational ankle fractures can be described by the number of malleoli involved (uni-, bi- and trimalleolar), and many ankle fractures occur in well-known, somewhat predictable patterns (Lauge-Hansen 1950, Lauge-Hansen 1954, Weber 1972). Traditional ankle fracture classifications are AO-Danis-Weber (Weber
1972) and Lauge-Hansen classification systems (Lauge-Hansen 1950). The Danis-Weber system has three categories based on the location of the distal fibular fracture in relation to the syndesmosis. Weber A fracture is infrasyndesmotic and considered stable. Weber B is transsyndesmotic and is variably stable. Weber C is suprasyndesmotic and is unstable. (Weber 1972) The Lauge-Hansen classification is based on cadaver experiments and each type is named by a double name. The first part of the name specifies the position of the foot and hindfoot at the moment of trauma (supination or pronation), and the second part describes the direction of the dislocating force (adduction, abduction, and external rotation) (Lauge-Hansen 1950). As a result, the classification scheme has four different injury patterns: supination-adduction (SA), supination external (SE) rotation, pronation-abduction (PA) and pronation external (PE) rotation. In general, Weber A corresponds to SA; Weber B to SE; Weber C1 to PA; and C2 to PE. The most common fracture mechanism is SER, accounting for 40–70% of all ankle fractures (Michelson et al. 1997). SER is also the fracture mechanism causing confusion, since the transsyndesmotic fracture can lead to instability of the ankle because of either partial or total rupture of the syndesmotic ligaments. The syndesmotic instability is not inevitably predicted from the fibular fracture level (Ebraheim et al. 2003, Nielson et al. 2004), and the primary determinants are the associated deltoid ligament injury or medial malleolar fracture (Michelson et al. 1992, Michelson et al. 2002, Ogilvie-Harris et al. 1994, Phillips et al. 1985, Sasse et al. 1999). The reliability of the Lauge-Hansen and the Weber systems has been questioned (Brage et al. 1998, Nielson et al. 1990, Rasmussen et al. 1993, Thomsen et al. 1991). Neither system can predict the outcome, and the effect of these systems in deciding whether to operate or not has been questioned. (Bauer et al. 1985b, Broos & Bisschop 1991, Cedell 1967, E gol et al. 2004, Gardner et al. 2006a, Haraguchi & Armiger 2009, Hughes et al. 1979, Lash et al. 2002, Michelson et al. 2007, Mont et al. 1992, Nielson et al. 2005, Pettrone et al. 1983).
Fig. 3. Ankle fracture classifications (Weber 1972 and Lauge Hansen 1950).

When a decision between operative and non-operative treatment is made, the stability of the fractured ankle is the most important factor. Stability-based ankle
Fracture classification systems have been developed to help the process (Michelson et al. 2007, Pakarinen et al. 2011a) (figure 4). The operative treatment is indicated only for fractures with injury to the tibiofibular syndesmosis and pathologic lateral movement of the talus in the ankle mortise (Michelson et al. 2007, Pakarinen et al. 2011a), which can only rarely be seen in preoperative radiographs (Beumer et al. 2004, Nielsen et al. 2004). Diagnosis often demands intraoperative tests that demonstrate instability (Jenkinson et al. 2005, Pakarinen et al. 2011a, Stark et al. 2007). Instability and dislocation of the distal fibula can also be rotational, which can be hard to detect since it does not always cause lateral translation of the talus on radiography (Donken et al. 2013). Yet it would be important to detect, since increased talar rotation might explain to some extent the suboptimal long-term outcome in ankle fractures (Bauer et al. 1985a, Donken et al. 2012, Horisberger et al. 2009, Sanders et al. 2012). Also, no normal values or criteria to evaluate rotation or dynamic movements of the distal tibiofibular joint in cross-sectional imaging had been published, and one of the aims was to focus on these issues.

Fig. 4. Decision tree for ankle fracture management (Pakarinen et al. 2011). (ORIF: open reduction internal fixation.)
2.3.2 Diagnosis

The diagnosis begins with history and physical examination. Swelling and pain can be caused by both ligamentous and bony injuries. The ankle is inspected for ecchymosis, swelling, and deformity. Active functions of the toes and ankle are tested. Maximal tenderness from the bones and soft tissues, as well as the bony crepitus, are tested. An anterior drawer test and talar tilt examinations can be used to get a rough opinion of the instability. The neurovascular status is tested, which consists of assessing arterial pulse (tibialis posterior, dorsalis pedis) and also testing for sensation (nervus suralis, nervus peroneus). Furthermore, the distal foot must be examined for Chopart or Lisfranc injuries, and the Achilles tendon assessed, since these can mimic ankle injury.

In the emergency department, most patients with an ankle injury undergo radiography, but less than 15% initially have a fracture (Clanton & Porter 1997, Hootman et al. 2007, Jensen et al. 1998, Michelson 1995, Sujitkumar et al. 1986, Thordarson 1996). A thorough clinical examination using the Ottawa ankle rules (pain in the malleolar region and bony tenderness along the distal 6 cm of the lateral or medial malleolus, or the inability to bear weight for four steps) may decrease the number of unwarranted radiographs by 30–40% (Bachmann et al. 2003, Stiell et al. 1995).

If a unimalleolar SER2-4 fracture is detected, the possible instability of the ankle mortise can appear as a diastase of the syndesmosis or lateral shift of the talus in radiographs (Edwards & DeLee 1984). Since dynamic incongruency is not revealed by radiographs, clinical tests that demonstrate possible instability should be made. An external rotation stress test or gravity stress radiographs can reveal if the MCS is wider than 5 mm, which indicates complete deltoid ligament injury (Gill et al. 2007, LeBa et al. 2015, Nortunen et al. 2015, Pankovich & Shivaram 1979, Weber et al. 2010). Syndesmosis integrity has traditionally been assessed by measuring tibiofibular clear space (TFCS) and tibiofibular overlap (TFO). Measurements have been made in radiographs, where incorrect positioning in imaging can lead to significant errors in interpretations of both TFCS and TFO (Beumer et al. 2004, Brage et al. 1998, Ebraheim et al. 1997b, Gourineni et al. 1999, Marmor et al. 2011, Miller et al. 2009, Nielson et al. 2005, Pneumaticos et al. 2002, Takao et al. 2001, Tochigi et al. 2006).

The decision of whether the syndesmosis should be operatively stabilized should be based on intraoperative dynamic stress testing after malleolar fractures are operatively fixed (Pakarinen et al. 2011a, Pakarinen et al. 2011b, van den
Bekerom 2011). There are several different stress tests, including the Cotton test, the external rotation stress test, the hook test, the standardized 7.5 Nm external rotation (ER) stress test, and the sagittal plane stress test (Candal-Couto et al. 2004, Hak et al. 2011, Jenkinson et al. 2005, Pakarinen et al. 2011a, Stoffel et al. 2009, van den Bekerom 2011). However, none of these tests alone can adequately detect instability (Pakarinen et al. 2011a), and that is why a combination of different tests should be used (van den Bekerom 2011). If sagittal translation or rotation of the fibula is achieved, the fibular translation or rotation tests are considered positive (Candal-Couto et al. 2004, Ogilvie-Harris et al. 1994).

2.3.3 Treatment

When a surgeon chooses between operative and non-operative treatment, the stability of the fractured ankle is the most important factor in decision-making regarding SER ankle fractures (Bauer et al. 1985a, Lauge-Hansen 1950, Michelson 1995, Pakarinen 2012, Phillips et al. 1985, Yde & Kristensen 1980). Unimalleolar ankle fractures can be treated non-operatively (Bauer et al. 1985a, Bauer et al. 1985b, Herscovici et al. 2007, Michelson 1995, Michelson et al. 2007, Pakarinen 2012, Ryd & Bengtsson 1992, van den Bekerom 2011, Yde & Kristensen 1980) if the talus does not move laterally in the mortise and an exact reduction can be maintained (Hoshino et al. 2012, Sanders et al. 2012, Tornetta et al. 2012, Zeegers et al. 1989). On the other hand, bi- and trimalleolar fractures are unstable injuries and normally treated operatively with rigid fixation using a plate and screws (Michelson et al. 2007, Pakarinen 2012). The lateral malleolus fracture is also treated operatively with a plate, and with two or three cortical screws on either side of the fracture (Hahn et al. 2007). If intraoperative testing reveals that syndesmosis stabilization is needed, techniques are usually based on transfixing the distal fibula to the tibia to allow soft tissue healing, but technical aspects of the fixation vary among surgeons (Bava et al. 2010, Cottom et al. 2009, Monga et al. 2008, Weening & Bhandari 2005).

2.3.4 Ligamentous injuries

Excessive inversion and internal rotation stress is the most common cause of ankle injury, with lateral sprains accounting for 85% of sports injuries (Ferran & Maffulli 2006, Garrick 1977, Hertel 2002, Maffulli & Ferran 2008). In the majority of lateral ankle sprains the ATFL is involved, since it is the weakest of the lat-
eral ligaments. The CFL is also involved in 50–75% and the PTFL in 10% of such injuries (Malliaropoulos et al. 2009). For ligamentous injuries, no standardized grading system exists, and long-term results vary.

When a fracture occurs, not only bones are damaged, but there is also variable soft tissue injury. Supination achieves tension on the lateral ankle structures and pronation on the medial structures. For anatomic reasons (taller lateral malleolus and stronger medial ligaments), the ankle is more resistant to eversion injury than inversion injury, but when excessive eversion occurs, there is substantial injury to ligaments and bony structures. In an SER fracture, the injury begins anterolaterally from ligamentous structures and proceeds around the ankle. Depending on the number of injured structures, injury results in severity stages 1 to 4. Eversion of the talus can lead to anterior syndesmosis (AITFL) injury (SER1) and distal oblique fracture of the fibula (SER2). Injury can progress posteriorly either to the capsule or to the posterior malleolus (SER3), and finally medially either to deltoid ligament tear or fracture of the medial malleolus (SER4). All of these changes can lead to instability of the ankle. On the medial side, isolated deltoid ligament tears are rare, but they are quite often seen in association with fibular and lateral malleolar fractures. In SER injuries, the deltoid ligament is one of the last structures to be damaged, but in pronation-eversion and pronation-abduction injuries, either the deltoid ligament or the medial malleolus is the initial structure that fails (Balduini & Tetzlaff 1982, Berkes et al. 2012, Brooks et al. 1981, Hughes et al. 1979, Jibri et al. 2013, Leeds & Ehrlich 1984, Magid et al. 1990, Meijer et al. 2015, Michelson et al. 1997, Michelson 1995).

2.4 Imaging of the ankle

Imaging is always based on clinical examination (Chapter 2.3.2). Effective radiation dose for ankle imaging is 1.5 μSv for the radiographic device (1.0 μSv lateral and 0.5 μSv anteroposterior), 1.4–14.3 μSv for cone-beam computed tomography (CBCT) and 21.4–25 μSv for multislice computed tomography (MSCT) (Koivisto et al. 2013, Koivisto et al. 2015, Ludlow & Ivanovic 2014, www.stuk.fi). An effective dose for one ankle radiograph equals less than 3 hours of background radiation, whereas one posteroanterior chest x-ray (0.03 mSv) equals 3 days of background radiation (in Finland, 3.2 mSv/year, www.stuk.fi).
2.4.1 Radiography

Radiography is one of the main tools in the primary assessment of ankle injuries because it is relatively quick and cheap, and provides low-dose images. Traditionally, three standard radiographic views (anteroposterior, mortise, and lateral) have been suggested (Goergen et al. 1977), but there is some debate regarding whether two or three radiographic views are necessary (Brage et al. 1998, Brandser et al. 2000, Cockshott et al. 1983, Vangsness et al. 1994, Wallis 1989). If clinical examination suggests a fracture, at least mortise (15-20° internal rotation) and lateral projections are the basic imaging set, which compared to all three standard radiographs are 98% accurate (Brage et al. 1998, Brandser et al. 2000, Cockshott et al. 1983, Vangsness et al. 1994, Winkler et al. 1990).

Since radiography is a two-dimensional imaging method, it has some limitations: the object of interest can be obscured by overlying structures, the anatomical dimensions can be difficult to describe due to geometric magnification, and the articular surfaces are often oblique with respect to the anatomical planes. Incorrect positioning in imaging can also lead to significant errors in interpretations and measurements (Beumer et al. 2004, Brage et al. 1998, Gourineni et al. 1999, Tochigi et al. 2006). Due to these limitations, a syndesmosis injury or the accuracy of reduction of the syndesmosis can be hard to evaluate (Ebraheim et al. 1997b, Marmor et al. 2011, Miller et al. 2009, Nielson et al. 2005, Pneumaticos et al. 2002, Takao et al. 2001). If only traditional radiographic evaluation of the syndesmosis is used (Harper & Keller 1989), it can even lead to unnecessary operative treatment (Shah et al. 2012).

2.4.2 Computed tomography and cone-beam computed tomography

A CT scan provides detailed information about bones and enables 3D reformation, which is needed preoperatively, especially with plafond injuries (Calhoun et al. 1999, Ferries et al. 1994, Magid et al. 1990, Meijer et al. 2015). Displacement of the fractures and congruence of the tibiotalar joint can be evaluated (Black et al. 2013, Calhoun et al. 1999, Michelson et al. 1992). Also, normal anatomy of the distal tibiofibular joint can be described (Ebraheim et al. 1997b, Elgafy et al. 2010, Mukhopadhyay et al. 2011), but no clinical studies using CT to evaluate the stability of the fractured ankle exist.

In CT imaging, a detector rotates around the patient to acquire images with a narrowly collimated, fan-shaped x-ray beam. Multidetector CT scanners use heli-
cal acquisition and a two-dimensional array of detector elements, which permits the CT scanner to acquire multiple slices while at the same time speeding up the imaging process (Haapamäki et al. 2004). It also enables large volume coverage in one rotation and the use of thin detector rows (less than 1 mm), which facilitates 3D image rendering. However, CT imaging has been associated with a disproportional increase in radiation doses (Brenner & Hall 2007). One method of minimizing radiation doses has been the implementation of CBCT technology.

The relatively simple mechanical configuration of CBCT has enabled the development of weight-bearing imaging of the extremities, and also intraoperative C-arm imaging. CBCT uses a large-area detector (e.g., less than 1,000 detector rows and columns covering ~30×30 cm²), and a pyramid-shaped x-ray beam (cone), which obtains fully volumetric data from multiple projections acquired in a single rotation about the patient without moving the patient through the scanner (Carrino et al. 2014, Tuominen et al. 2013). Visualization is not always as good as that produced in an MSCT. This is due to streaks associated with x-ray scatter in thicker regions of the patient (e.g., the knee), beam hardening about the cortical bone (e.g., the femoral shaft), and cone-beam artifacts at joint space surfaces oriented along the scanning plane (e.g., the interphalangeal joints) (Carrino et al. 2014), but the image quality is usually sufficient for bone imaging (Demehri et al. 2015).

A few studies have used cross-sectional imaging to investigate the normal anatomy of the ankle and malreduction of syndesmosis (Dikos et al. 2012, Ebraheim et al. 1997b, Elgafy et al. 2010, Gardner et al. 2006b, Mukhopadhyay et al. 2011, Sagi et al. 2012, Sora et al. 2004) and to evaluate asymmetry between ankles (Dikos et al. 2012, Mukhopadhyay et al. 2011). Before the current studies, only the study of Dikos et al. evaluated bilateral, uninjured ankles. Previous studies have several methodological differences, including the measurement points used, the use of cadavers in some studies, and the method of evaluating only one leg (Ebraheim et al. 1997a, Elgafy et al. 2010, Gardner et al. 2006b).

One of the main advantages in CT imaging compared to radiography is the ability to see internal derangements of the joint. Especially in operative decision-making, traditional radiography-based measurements, such as TFCS or TFO, should be avoided, since those vary considerably with ankle rotation. With CT, the same principle with rotation can lead to similar errors if projectional measurements are used (Beumer & Swierstra 2003, Beumer et al. 2004, Pneumaticos et al. 2002). To avoid any inaccuracies caused by possible variation in positioning
of the ankle for imaging or image reading, cross-sectional imaging with standardized measurement points and true distance measurements was used in this thesis.

Since the lower extremities are normally under weight-bearing conditions, imaging in a supine position can give misleading information (Draper et al. 2011, Haleem et al. 2014, Thawait et al. 2015). Previously, weight-bearing radiographs, despite their limitations, have been the only functional imaging method in clinical practice when studying the knee, ankle, and foot. In order to correctly evaluate instability, degeneration, or post-traumatic conditions, the normal anatomy and dynamics of the joint must be known. These studies focused on investigating these issues in both supine CT imaging and WBCT imaging in the standing position and under rotational stress.

### 2.4.3 Ultrasound imaging

Ultrasound (US) imaging can be used on the ankle to evaluate normal anatomic soft tissue structures and ligament integrity. It also allows dynamic maneuvers, which may improve the visibility of normal ligaments and improve detection of subluxations or tears. Other abnormalities, such as tendinopathy, tenosynovitis, ganglia, bursitis or joint effusion can also be seen. US imaging is less time-consuming, costs less, and is widely available. Another benefit is that US is free of ionizing radiation (Allison & Nazarian 2010, Bianchi et al. 2005, Klauser et al. 2012). However, US is limited to imaging of superficial soft tissues; deeper pathology such as a bone bruising, hidden fractures, or cartilage lesions cannot be seen. Often, other imaging modalities (i.e., radiography and magnetic resonance imaging) are needed to examine the associated findings.

### 2.4.4 Magnetic resonance imaging

TFO, and the MCS did not correlate with ligamentous injuries that were shown on concurrent MRI studies (Hermans et al. 2011). Availability of the MRI may also be a problem, as well as the long imaging time, especially with trauma patients. MRI is also relatively expensive, and in postoperative imaging, metallic implants may cause significant artefacts (Singh et al. 2014).
3 Purpose of the study

The purpose of this study was to assess intersubject and intrasubject variation of the distal tibiofibular syndesmosis and upper ankle joint on CT and WBCT scans. Particular aims were to:

I Assess the distal tibiofibular syndesmosis on non-weightbearing CT scans to provide standardized measures of the syndesmosis in cross-sectional imaging.

II Investigate the normal anatomy and rotational dynamics of the distal tibiofibular joint in upright WBCT in maximal internal and external rotations of the ankle.

III Investigate the rotational dynamics of the talus in the upper ankle joint using WBCT in the standing position and under rotational stress.
4 Materials and methods

4.1 Study populations

4.1.1 Non-weightbearing computed tomography of the syndesmosis (I)

Study I initially had 68 patients (136 ankles) from August 2009 to October 2012, and it was a retrospective study. All patients needed lower extremity torsion CT covering the ankle joint. If there was any history of ankle fracture or ligamentous ankle injury, patients were excluded. If there was any suspicion of a condition that could lead to altered lower limb function and distal tibiofibular anatomy, patients were excluded. Four patients were completely excluded (i.e., both ankles) due to deformities (juvenile scoliosis, spastic diplegia, cerebral palsy, and lipomeningomyelocele). One ankle was excluded in 21 patients due to a previous tibial fracture. After exclusion, data consisted of 64 patients and 107 ankles. Patients included 35 (55%) females, and 29 (45%) males; the mean age was 44 years (SD 17, age range 14–88). A total of 43 patients (86 ankles) were scanned bilaterally. Patient data and CT scans were collected from the university hospital’s information system. Prior to imaging, all patients were seen by an orthopedic surgeon. The patients had existing conditions, which led to the initial scan to evaluate their lower limb torsion profile. Conditions included operatively treated contralateral ankle fracture (n = 21, only uninjured ankles were included in the study), femoral fracture/osteotomy (n = 12), acquired foot deformity (n = 8), knee pain (n = 6), patellar dislocation (n = 5), miserable malalignment (n = 3), ankle tendon problems (n = 3), postoperative knee problem (n = 2), hip pain (n = 2), congenital hip dislocation (n = 1), and pigmented villonodular synovitis (n = 1).

4.1.2 Weightbearing cone-beam computed tomography of the syndesmosis and ankle (II, III)

In Study II and Study III, all subjects were recruited from the university hospital staff; they were healthy volunteers with non-athletic backgrounds. A total of 32 subjects participated in the study from March 2014 to April 2014. There were 10 males and 8 females in the 26–36 age group (n=18), and 7 males and 7 females in the 60–64 age group (n=14). Before any study-specific procedures were per-
formed, an orthopedic surgeon examined the posture and alignment of the foot, and all subjects provided written informed consent. All ankles had excellent functional condition (Olerud-Molander score of 100). Exclusion criteria in the study included history of ankle fracture, ligamentous ankle injury, malalignment or deformity of the lower leg, neuropathy, or previous foot or ankle surgery leading to altered ankle anatomy or function.

4.2 Imaging methods

4.2.1 Non-weightbearing computed tomography of the syndesmosis (I)

All CT scans were obtained using the bone algorithm (Siemens Somatom Sensation 64, Germany). The scan parameters were: field of view, 26 cm; peak kilovoltage (kVp), 120 kV; quality ref. mAs, 90; rotation time, 1.0 s, and slice thickness, 0.6 mm. The tibiofibular syndesmosis and ankle was covered with continuous sections and images were obtained without gantry tilt in the axial plane. An isotropic high-resolution protocol was used with a resolution of 0.51 mm and 512×512 matrix. Bone window and 1 mm thick slices were used for measurements.

4.2.2 Weightbearing cone-beam computed tomography of the syndesmosis and ankle (II, III)

Each subject had six low-dose CBCT scans (effective dose 6.0 μSv each, comparable to 2–4 radiographs of the ankle) (Koivisto et al. 2015). Both ankles were imaged in the neutral position and at maximal internal and external rotation on the same day (imaging described in detail in Figure 5). The tibiofibular syndesmosis and ankle was covered with continuous sections and images were obtained in the axial plane in all three rotation positions using WBCT (Planmed Verity Extremity, Planmed Oy, Finland; tube voltage, 96 kV; tube current, 8 mAs; computed tomography dose index [CTDI] vol 4.32 mGy; matrix, 160×160×130; voxel size, 0.4×0.4×0.4 mm³).
Fig. 5. Ankle posture and positioning in neutral position (A), in external rotation of the talus (B), and in internal rotation of the talus (C) in weight-bearing imaging.

In A, the subject was instructed to stand as normally as possible, bare-footed with pressure neutrally on the foot, without pelvic or lower leg rotation. The other foot rested lightly on the gantry. (Figure A)

In B, the subject was asked to rotate the whole body as much as possible from the shoulders to the pelvis. The lower limb turned inwards (tibia in internal rotation). The distal metatarsal line of the foot and medial side of the sole were still in contact with the base (Figure B).

In C, the subject was asked to rotate the lower limb and whole body outwards (tibia in external rotation). The distal metatarsal line and the lateral side of the sole were still in contact with the base (Figure C). Imaging was performed when subjects expressed pain in the ankle, knee or hip to achieve maximal degree of rotation. Two subjects were tested with electronic steelyard for the rotational power. Rotation power was applied with mean force of 200 N resulting in a moment of 30 Nm.
4.3 Image analysis and measurement methods

4.3.1 Non-weightbearing and weightbearing computed tomography of the syndesmosis (I, II)

The CT measurements were made at wide window and level settings (1,400 window, 300 level) on a clinical workstation (Neaview, Neagen, Oulu, Finland). CT planes were rotated exactly perpendicular to the tibial plafond, and measurements were obtained 1 cm above the joint space (Figure 6) at the level of the anterior tibial tubercle, since the fibular incisura is best defined at this level (Beumer & Swierstra 2003, Elgafy et al. 2010, Jenkinson et al. 2005). To provide comparable measurements, the level was consistent with previous CT studies (Dikos et al. 2012, Ebraheim et al. 1997b, Gardner et al. 2006b, Mukhopadhyay et al. 2011). The measurements obtained are depicted in Figures 7–12.

Two musculoskeletal radiologists made the measurements blinded to the patients’ data. The investigators (the senior musculoskeletal radiologist and the principal investigator) recorded the results from a randomly ordered list two times at one-week intervals, blinded to the previous measurements. Twenty cases were randomly chosen for inter- and intraobserver reliability analyses.

![Fig. 6. The measurements were taken from reformatted axial CT planes rotated exactly parallel to the tibial plafond and obtained 10 mm above the tibial subchondral bone. (I, II). (Printed with permission: FAI 2016, Jun;37(6)625-35. Sage Journals©)](image-url)
Fig. 7. Length of the tibial incisura (LI), Sagittal translation of the fibula (ST) (II, III).

Fig. 8. Anterior width (AW) and posterior width (PW) of the tibiofibular syndesmosis. (I, II).

Fig. 9. The depth of the incisura (DI) (I).
Fig. 10. The narrowest part of the incisura (NI) (I).

Fig. 11. Tibiofibular clear space (TFCS) (II).

Fig. 12. Rotation of the fibula (RO) (II).
4.3.2 Weightbearing cone-beam computed tomography of the upper ankle joint (III)

Researchers evaluated the CT data on a clinical workstation using bone window reformations for measurement. All measurements (with the exception of the talar tilt) were taken from the axial plane, which was rotated exactly parallel to the tibial plafond. The measurements were obtained one slice above the intercollicular groove of the medial malleolus.

The measurement method is described in detail in Figure 13 and the obtained measurements obtained are depicted in Figure 14. The tangential line of the medial malleolus (medial malleolar tangent, MMT) (Figure 14A) formed a base for most of the measurements. Rotation of the talus was measured from the angle between the MMT (orientation of the ankle) and the anterior surface of the talus (orientation of the talus) (Figure 14A). The medial clear space (MCS) was measured between the parallel lines of the medial tangent of the talus and the deepest point of the tibial subchondral bone. Both lines were parallel to the MMT (Figure 14B). The anterior (AW) and posterior (PW) widths of the tibiotalar joint were measured between the subchondral bone of the talus and the MMT (Figure 14C and D). The translation of the talus (TrT) was measured from the anterior surface of the medial malleolus to a line tangential to the anterior surface of the talus. Positive values indicated the anterior position of the anteromedial corner of the talus compared to the medial malleolus while negative values indicated the posterior position of the anteromedial corner of the talus (Figure 14C and D). From the coronal reformat, the talar tilt was measured from an angle between the plafond of the talus and the tibia. Positive values indicated eversion and negative values inversion of the talus (Figure 14E). All measurements were performed on the neutral, external rotation and internal rotation images. The mean changes between positions (i.e., talar dynamics in rotation) were calculated from static measurement points, for example external rotation vs. internal rotation. The differences between age groups and sexes, and bilateral intrasubject variation were also calculated. Investigators were blinded to the patients’ data and made all the measurements from a randomly ordered list. For the inter- and intraobserver reliability analyses, data was measured from 20 randomly selected cases. For intraobserver reliability, data were measured twice with a week term. Measures were compared between investigators for interobserver reliability analyses.
Fig. 13. A-C. Image analysis method. The axial (A), sagittal (B), and coronal (C) planes were perpendicular and rotated simultaneously. The axial plane was first rotated (1) parallel to the subchondral bone with medial malleolus (MMT) sagittally. From this axial slice, the center of the talus (2) was determined. Third, from the sagittal plane, the center of the posterior and anterior margins of the tibia (3) was determined and the axial plane accordingly tilted. The coronal plane was then rotated so that the axial plane (4) was parallel to the tibial plateau. From this slice the talar tilt was measured. The axial slice was now parallel to the tibial plateau and the talar dome, and measurements were made (5) 1 mm above the intercollicular groove of the medial malleolus (arrow). (Printed with permission: J Bone Joint Surg Am. 2016;98:568-75. Wolters Kluwer Heath Lippincot Williams & Wilkins©)
Fig. 14. A-E. CT measurements. MMT is the dotted line, and arrow shows the angle of the talus for the rotation of the talus (RO) measurements (A). Medial clear space (MCS) (B). In image C, there is internal rotation of the talus. Translation of the talus is in posterior direction (TrT). Anterior (AW) and posterior width (PW) of the tibiotalar joint (C). In image C, there is external rotation of the talus. Translation of the talus is in anterior direction (TrT), (AW) and (PW) of the tibiotalar joint (D). Talar tilt, arrow shows the angle of the talus (E). (Printed with permission: J Bone Joint Surg Am. 2016;98:568-75. Wolters Kluwer Heath Lippincot Williams & Wilkins©)
4.4 Statistical methods

4.4.1 Non-weightbearing computed tomography of the syndesmosis (I)

The continuous measurements are presented as means and standard errors (SE). Categorical data are presented as frequencies and proportions. Independent samples t-test (for continuous variables) or chi-square test (for categorical variables) was used to evaluate the differences between genders. Differences between right and left ankles were evaluated using paired samples t-test. P-values less than 0.05 were considered statistically significant. For continuous variables, the inter- and intraobserver reliabilities were estimated by calculating the intraclass correlation coefficient (ICC, single measurements) and for categorical variables by kappa. ICC values were interpreted according to the guidelines proposed by Schrout and Landis as follows: 0.00–0.10 virtually none, 0.11–0.40 slight, 0.41–0.60 fair, 0.61–0.80 moderate, and 0.81–1.00 substantial (Landis & Koch 1977, Shrout 1998). Kappa was interpreted according to Landis and Koch as follows: 0.00 to 0.20 slight, 0.21 to 0.40 fair, 0.41 to 0.60 moderate, 0.61 to 0.80 substantial, and above 0.80 indicated almost perfect agreement (Landis & Koch 1977). PASW Statistics (SPSS Ltd, Hong Kong), version 18.0. was used to conduct statistical analyses.

4.4.2 Weightbearing cone-beam computed tomography of the syndesmosis and tibiotalar joint (II, III)

The influence of age was evaluated using a linear regression analysis and differences between sexes using an independent samples t-test. One ankle from each subject was randomly selected to sex and age analyses and for summary statistics. The differences between bilateral ankles and change of the measurements between internal and external rotation were evaluated using paired samples t-test. A p-value < 0.05 was considered significant. To correct for multiple comparisons, Benjamini-Hochberg correction was used. The summary statistics are presented in Figures 15 and 17 as box plot (median, upper and lower quartile and range). The intraclass correlation coefficient (ICC, single measurements) was calculated to estimate the inter- and intraobserver reliabilities for the continuous variables. Interpretation of the ICC values was carried out according to the guidelines proposed by Landis and Shrout (Landis & Koch 1977, Shrout 1998). All analyses
were performed using SPSS Statistics for Windows, version 22.0 (released 2010; IBM, Armonk, NY).
5 Results

5.1 Position of the fibula (I, II)

In NWBCT (I), the fibula was situated either anteriorly or centrally in the tibial incisura in 97% (104) of the cases (Table 1), and in neutrally-loaded ankle WBCT (II) anteriorly in 88% of subjects (Table 2). When the talus was rotated externally, the fibula was located in the posterior part of the incisura in 40% of subjects. If there was internal rotation, none of the subjects exhibited posterior location.

Table 1. Sagittal translation (ST) of the fibula in NWBCT.

<table>
<thead>
<tr>
<th>Sagittal translation</th>
<th>Gender</th>
<th>p^1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td></td>
<td>n (%)</td>
<td>n (%)</td>
</tr>
<tr>
<td>No translation^2</td>
<td>10 (23)</td>
<td>22 (34)</td>
</tr>
<tr>
<td>Anterior^2</td>
<td>33 (77)</td>
<td>39 (61)</td>
</tr>
<tr>
<td>Posterior^2</td>
<td>0 (0)</td>
<td>3 (5)</td>
</tr>
<tr>
<td>Total n</td>
<td>43</td>
<td>64</td>
</tr>
</tbody>
</table>

^1 Significance from Pearson's Chi-square test, ^2 Anterior or posterior translation. No translation equals central positioning
ns = no significant difference,
* = p < 0.05, *** p < 0.01, **** p < 0.001
Table 2. Sagittal translation (ST) of the fibula in WBCT.

<table>
<thead>
<tr>
<th>Sagittal translation</th>
<th>Gender</th>
<th>p(^1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
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<tr>
<td></td>
<td>n (%)</td>
<td>n (%)</td>
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<tr>
<td>Neutral position</td>
<td></td>
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<tr>
<td>ST of the fibula</td>
<td></td>
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</tr>
<tr>
<td>Anterior</td>
<td>32 (94)</td>
<td>26 (87)</td>
</tr>
<tr>
<td>Central</td>
<td>2 (6)</td>
<td>3 (11)</td>
</tr>
<tr>
<td>Posterior</td>
<td>0 (0)</td>
<td>1 (4)</td>
</tr>
<tr>
<td>External rotation of the talus</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>ST of the fibula</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>15 (44)</td>
<td>14 (47)</td>
</tr>
<tr>
<td>Central</td>
<td>5 (15)</td>
<td>4 (13)</td>
</tr>
<tr>
<td>Posterior</td>
<td>14 (41)</td>
<td>12 (40)</td>
</tr>
<tr>
<td>Internal rotation of the talus</td>
<td>ns</td>
<td></td>
</tr>
<tr>
<td>ST of the fibula</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anterior</td>
<td>32 (94)</td>
<td>27 (90)</td>
</tr>
<tr>
<td>Central</td>
<td>2 (6)</td>
<td>3 (10)</td>
</tr>
</tbody>
</table>

\(^{1}\)Significance from Pearson’s Chi-square test  
ns = no significant difference,  
* = p < 0.05, ** = p < 0.01, *** = p < 0.001

5.2 Measurements

5.2.1 Measurements of syndesmosis (I, II)

Static measurements of the syndesmosis

In NWBCT (I), the mean anterior width of syndesmosis was 2.8 mm (SE 0.09, range 0.9–5.3) and posterior width 5.1 mm (SE 0.15, range 2.7–9.1) (Table 3). Considering the traditional cut-off point of 2 mm, the mean difference between the posterior and anterior width of the incisura (PW-AW) was 2.2 mm (SE 0.18). A difference was seen between genders (males 2.7 mm (SE 0.32), females 1.9 mm (SE 0.20), p = 0.023, t-test).

All static WBCT (II) measurements are shown in Table 4 (both neutral and rotational measurements) and in Figure15. There was large intersubject variation in all of the measurements.
Table 3. Summary of NWBCT(I) measurements of the syndesmosis (units in millimeters).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Gender</th>
<th>p¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males, n = 43</td>
<td>Females, n = 64</td>
</tr>
<tr>
<td></td>
<td>Mean (SE)</td>
<td>Mean (SE)</td>
</tr>
<tr>
<td>Length of the tibial incisura</td>
<td>24.0 (0.33)</td>
<td>20.9 (0.24)</td>
</tr>
<tr>
<td>Depth of the tibial incisura</td>
<td>4.4 (0.23)</td>
<td>3.9 (0.14)</td>
</tr>
<tr>
<td>Sagittal translation</td>
<td>1.6 (0.18)</td>
<td>1.1 (0.13)</td>
</tr>
<tr>
<td>AW, of the incisura</td>
<td>2.9 (0.13)</td>
<td>2.8 (0.12)</td>
</tr>
<tr>
<td>PW, of the incisura</td>
<td>5.6 (0.28)</td>
<td>4.7 (0.15)</td>
</tr>
<tr>
<td>Narrowest part of the incisura</td>
<td>1.8 (0.11)</td>
<td>1.9 (0.09)</td>
</tr>
</tbody>
</table>

¹ Significance from independent samples t-test
ns = no significant difference,
* = p < 0.05, ** = p < 0.01, *** = p < 0.001
Table 4. Summary of WBCT(II) measurements of the syndesmosis (units in millimeters).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Total n = 64 (100%)</th>
<th>Gender</th>
<th>Males n = 34 (53%)</th>
<th>Females n = 30 (47%)</th>
<th>p</th>
<th>Younger n = 36 (56%)</th>
<th>Older n = 28 (44%)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>range</td>
<td>Mean</td>
<td>SD</td>
<td>range</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Length of the tibial incisura, mm</td>
<td>21.7</td>
<td>2.32</td>
<td>16.9–27.2</td>
<td>22.9</td>
<td>2.18</td>
<td>16.9–27.2</td>
<td>20.4</td>
<td>1.70</td>
</tr>
<tr>
<td>Depth of the tibial incisura, mm</td>
<td>4.4</td>
<td>1.03</td>
<td>2.4–6.6</td>
<td>4.8</td>
<td>0.99</td>
<td>2.4–6.6</td>
<td>4.0</td>
<td>0.94</td>
</tr>
<tr>
<td>Neutral position</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST, mm</td>
<td>1.4</td>
<td>0.89</td>
<td>-2.1–3.3</td>
<td>1.5</td>
<td>0.74</td>
<td>0.0–3.0</td>
<td>1.3</td>
<td>1.04</td>
</tr>
<tr>
<td>AW, of the incisura, mm</td>
<td>3.0</td>
<td>0.88</td>
<td>1.2–5.5</td>
<td>3.1</td>
<td>0.92</td>
<td>1.7–5.5</td>
<td>2.8</td>
<td>0.82</td>
</tr>
<tr>
<td>PW, of the incisura, mm</td>
<td>5.7</td>
<td>1.31</td>
<td>3.2–9.0</td>
<td>6.1</td>
<td>1.23</td>
<td>4.1–9.0</td>
<td>5.3</td>
<td>1.28</td>
</tr>
<tr>
<td>TFCS, mm</td>
<td>3.7</td>
<td>1.01</td>
<td>1.7–6.2</td>
<td>4.0</td>
<td>0.95</td>
<td>2.1–6.2</td>
<td>3.3</td>
<td>0.96</td>
</tr>
<tr>
<td>Rotation, degrees</td>
<td>54.3</td>
<td>5.7</td>
<td>40–65</td>
<td>54.5</td>
<td>5.7</td>
<td>43–65</td>
<td>54.0</td>
<td>5.8</td>
</tr>
<tr>
<td>External rotation of the talus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST, mm</td>
<td>0.1</td>
<td>1.00</td>
<td>-1.9–2.6</td>
<td>0.1</td>
<td>0.82</td>
<td>-1.2–1.6</td>
<td>0.1</td>
<td>1.20</td>
</tr>
<tr>
<td>AW, of the incisura, mm</td>
<td>4.1</td>
<td>0.91</td>
<td>2.3–5.9</td>
<td>4.4</td>
<td>0.90</td>
<td>2.7–5.9</td>
<td>3.9</td>
<td>0.87</td>
</tr>
<tr>
<td>PW, of the incisura, mm</td>
<td>4.6</td>
<td>1.22</td>
<td>2.0–7.5</td>
<td>4.8</td>
<td>0.94</td>
<td>2.9–6.5</td>
<td>4.4</td>
<td>1.47</td>
</tr>
<tr>
<td>TFCS, mm</td>
<td>3.8</td>
<td>1.00</td>
<td>1.8–6.5</td>
<td>4.1</td>
<td>0.84</td>
<td>2.6–6.5</td>
<td>3.4</td>
<td>1.04</td>
</tr>
<tr>
<td>Rotation, degrees</td>
<td>51.7</td>
<td>5.4</td>
<td>37–60</td>
<td>51.9</td>
<td>4.3</td>
<td>43–59</td>
<td>51.5</td>
<td>6.4</td>
</tr>
<tr>
<td>Internal rotation of the talus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST, mm</td>
<td>1.6</td>
<td>0.80</td>
<td>0.0–3.3</td>
<td>1.7</td>
<td>0.69</td>
<td>0.0–3.2</td>
<td>1.6</td>
<td>0.91</td>
</tr>
<tr>
<td>AW, of the incisura, mm</td>
<td>2.9</td>
<td>0.92</td>
<td>0.0–4.9</td>
<td>3.0</td>
<td>0.93</td>
<td>1.3–4.8</td>
<td>2.8</td>
<td>0.92</td>
</tr>
<tr>
<td>PW, of the incisura, mm</td>
<td>6.1</td>
<td>1.22</td>
<td>3.5–8.4</td>
<td>6.4</td>
<td>1.17</td>
<td>3.7–8.4</td>
<td>5.7</td>
<td>1.19</td>
</tr>
<tr>
<td>TFCS, mm</td>
<td>3.8</td>
<td>1.00</td>
<td>1.7–6.4</td>
<td>4.1</td>
<td>0.96</td>
<td>2.1–6.2</td>
<td>3.5</td>
<td>0.97</td>
</tr>
<tr>
<td>Rotation, degrees</td>
<td>55.0</td>
<td>5.7</td>
<td>40–65</td>
<td>55.1</td>
<td>5.1</td>
<td>43–63</td>
<td>54.9</td>
<td>6.5</td>
</tr>
</tbody>
</table>

1 significance from independent samples t-test, difference between genders, 2 significance from independent samples t-test, difference between age groups, 3 ns = no significant difference, *** p < 0.01, ** p < 0.001
5.2.2 Measurements of the tibiotalar joint (III)

Both static and rotational WBCT (III) measurements are shown in Table 5 and Figure 16. In the neutral position, females exhibited a narrower MCS compared to males (mean 2.3 mm vs. 2.6 mm, p < 0.01). Females also had significantly smaller AW (mean 2.1 mm vs. 1.7 mm, p < 0.001) and PW (mean 2.9 mm vs. 3.4 mm, p < 0.01) than males in the neutral position, although the variations in the measurements were not directly proportional to the joint or bone size (data not shown).

There was no significant difference between genders in terms of talar rotation, TrT or talar tilt. None of the measured values exhibited significant differences between age groups. In internal rotation, females had significantly smaller PW (mean 3.0 mm vs. 3.6 mm, p < 0.01) values. In external rotation, the talar rotation was significantly smaller in females (mean 8.4 degrees vs. 12.0 degrees, p < 0.05), as well as the AW (mean 2.6 mm vs. 3.6 mm, p < 0.001). The only significant difference in rotations between the age groups was the talar tilt. In internal rotation, the younger age group had a mean talar tilt of 0.6 degrees inversion and the older age group 0.1 degrees eversion (p < 0.05). In external rotation, the mean talar tilt values were 1.1 vs. 2.2 degrees (p < 0.01) respectively.
Table 5. Summary of WBCT(III) measurements of the tibiotalar joint, all subjects, n = 64 ankles.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean</th>
<th>SD</th>
<th>Range</th>
<th>95% CI of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Lower</td>
<td>Upper</td>
</tr>
<tr>
<td>Internal rotation of the talus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>0.2</td>
<td>5.7</td>
<td>-14.0(^1)</td>
<td>18.0</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>2.5</td>
<td>0.6</td>
<td>1.3</td>
<td>4.5</td>
</tr>
<tr>
<td>AW, mm</td>
<td>2.2</td>
<td>0.6</td>
<td>1.1</td>
<td>4.9</td>
</tr>
<tr>
<td>PW, mm</td>
<td>3.3</td>
<td>0.8</td>
<td>1.4</td>
<td>5.5</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>-0.1</td>
<td>1.9</td>
<td>-3.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>-0.3</td>
<td>1.2</td>
<td>-3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Neutral position</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>1.4</td>
<td>4.7</td>
<td>-11.0</td>
<td>11.0</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>2.4</td>
<td>0.5</td>
<td>1.3</td>
<td>4.1</td>
</tr>
<tr>
<td>AW, mm</td>
<td>2.4</td>
<td>0.5</td>
<td>1.5</td>
<td>3.7</td>
</tr>
<tr>
<td>PW, mm</td>
<td>3.2</td>
<td>0.6</td>
<td>1.8</td>
<td>5.0</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>0.1</td>
<td>1.4</td>
<td>-2.3</td>
<td>4.3</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>-0.1</td>
<td>1.2</td>
<td>-5.0</td>
<td>2.2</td>
</tr>
<tr>
<td>External rotation of the talus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>10.3</td>
<td>5.7</td>
<td>-3.8</td>
<td>21.0</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>2.3</td>
<td>0.6</td>
<td>0.9</td>
<td>4.2</td>
</tr>
<tr>
<td>AW, mm</td>
<td>3.1</td>
<td>0.8</td>
<td>1.6</td>
<td>4.8</td>
</tr>
<tr>
<td>PW, mm</td>
<td>2.8</td>
<td>0.8</td>
<td>1.0</td>
<td>4.9</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>2.8</td>
<td>2.0</td>
<td>-0.8</td>
<td>7.5</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>1.5</td>
<td>1.4</td>
<td>-1.8</td>
<td>5.1</td>
</tr>
</tbody>
</table>

\(^1\) Representation of negative values are explained in Material and Methods

Fig. 16. WBCT(III) measurements of the tibiotalar joints. (Printed with permission: J Bone Joint Surg Am. 2016;98:568-75. Wolters Kluwer Heath Lippincot Williams & Wilkins\(^\circ\))
5.3 Difference in measurements between rotations (II, III)

5.3.1 Syndesmosis (II)

The measurements between static positions were calculated to observe the rotation dynamics of the tibiofibular joint (Table 6, Figure 17) (II). Between external and internal rotations, mean changes were: ST 1.5 mm (SD: 0.9; 95% CI: (1.2 – 1.8); p = 0.005), AW 1.3 mm (1.0; (0.9, 2.17); p = 0.0025), PW 1.5 mm (0.8; (1.0, 1.6); p = 0.0017), TFCS 0.0 mm (0.5; (-0.1, 0.3); p > 0.05), and rotation of the fibula 3.2 degrees (2.8; (2.1, 4.2); p = 0.00125). There was no significant difference between age or sexes (data not shown).

Table 6. Motion of the fibula in ankle rotation (II).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean Change</th>
<th>SD</th>
<th>Range</th>
<th>95% CI of the Difference</th>
<th>p 1,2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal - External rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST, mm</td>
<td>1.5</td>
<td>0.9</td>
<td>-0.8–3.4</td>
<td>1.3</td>
<td>1.8</td>
</tr>
<tr>
<td>AW, of the incisura, mm</td>
<td>-1.3</td>
<td>1.0</td>
<td>-3.4–0.5</td>
<td>-1.5</td>
<td>-1.0</td>
</tr>
<tr>
<td>PW, of the incisura, mm</td>
<td>1.5</td>
<td>1.0</td>
<td>-1.8–3.6</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>TFCS, mm</td>
<td>0.0</td>
<td>0.6</td>
<td>-1.1–1.9</td>
<td>-0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Rotation, degrees</td>
<td>3.3</td>
<td>3.1</td>
<td>-5–11</td>
<td>2.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

1 Significance from paired t-test, difference between positions, 2 no significant difference, * = p < 0.05,
** = p < 0.01, *** = p < 0.001
5.3.2 Tibiotalar joint (III)

To observe the rotation dynamics of the tibiotalar joint (III), measurements between static positions were calculated as shown in Table 7, Figure 18. Between the external and internal rotation of the talus, the mean rotation of the talus was 10 degrees (SD: 5.8; 95% CI: (8, 12)), the talar tilt was 2.0 degrees (1.5; (1.4, 2.5)), the mean difference at MCS was 0.2 mm (0.5; (-0.4, -0.1)), AW was 0.9 mm (0.8; (0.6, 1.2)), PW was 0.4 mm (0.9; (-0.8, -0.1)), TrT was 3.0 mm (2.2; (2.2, 3.8)). Sex and age did not affect the results of the measurements between positions (data not shown).
Table 7. Difference between rotations in measurements of the tibiotalar joint (III).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Mean Change</th>
<th>SD</th>
<th>Range</th>
<th>95% CI of the Difference</th>
<th>p 1,2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>External - Internal rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>10.1</td>
<td>5.7</td>
<td>-0.7</td>
<td>21.9</td>
<td>8.7</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>-0.2</td>
<td>0.5</td>
<td>-1.2</td>
<td>1.0</td>
<td>-0.3</td>
</tr>
<tr>
<td>AW, mm</td>
<td>0.9</td>
<td>0.7</td>
<td>-1.4</td>
<td>2.8</td>
<td>0.7</td>
</tr>
<tr>
<td>PW, mm</td>
<td>-0.5</td>
<td>0.8</td>
<td>-2.3</td>
<td>1.3</td>
<td>-0.7</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>2.9</td>
<td>2.2</td>
<td>-2.6</td>
<td>7.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>1.8</td>
<td>1.4</td>
<td>-0.8</td>
<td>5.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

1 Significance from paired t-test, difference between positions, * = p < 0.05, ** = p < 0.01, *** = p < 0.001

Fig. 18. Difference in measurements of the tibiotalar joint between rotations (III) (Talar rotation, talar tilt, MCS, AW, PW, TrT) (Printed with permission: J Bone Joint Surg Am. 2016;98:568-75. Wolters Kluwer Heath Lippincot Williams & Wilkins©)
5.4 Intrasubject variation between ankles

5.4.1 Syndesmosis (I, II)

In NWBCT of the syndesmosis (I), there was asymmetry between ankles in 43 subjects (Table 8).

Table 8. Asymmetry between ankles in 43 subjects (units in millimeters).

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Ankle</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td>Length of the tibial incisura</td>
<td>21.3</td>
<td>21.9</td>
</tr>
<tr>
<td>Depth of the tibial incisura</td>
<td>3.9</td>
<td>3.9</td>
</tr>
<tr>
<td>AW, of the incisura</td>
<td>2.7</td>
<td>2.9</td>
</tr>
<tr>
<td>PW, of the incisura</td>
<td>5.1</td>
<td>5.3</td>
</tr>
<tr>
<td>Narrowest part of the incisura</td>
<td>1.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Sagittal transition</td>
<td>1.4</td>
<td>1.3</td>
</tr>
</tbody>
</table>

ns = no significant difference,
* = p < 0.05, ** = p < 0.01, *** = p < 0.001

In neutrally loaded WBCT of the syndesmosis (II), in static measurements there was some minor bilateral variation. In internal rotation there was significant asymmetry in AW (0.6 mm; SD 0.9; 95% CI (0.2, 0.9); p = 0.005), in neutral position in ST (0.5 mm; 0.9; (0.2, 0.9); p = 0.0075) and PW (0.8 mm; 0.9; (0.5, 1.1); p = 0.005), and in external rotation in PW (0.5 mm; 0.6; (0.3, 0.8); p = 0.005). In the dynamic measurements of the syndesmosis, there was intrasubject (i.e., bilateral) asymmetry only in PW (0.6 mm; 1.0; (0.2, 0.9); p = 0.01) (Table 9).
Table 9. Asymmetry between ankles, WBCT measurements of the syndesmosis (II).

<table>
<thead>
<tr>
<th>Measurement, Right - Left</th>
<th>Mean Difference</th>
<th>SD</th>
<th>95% CI of the Difference</th>
<th>p&lt;sup&gt;1,2&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of the tibial incisura, mm</td>
<td>0.2</td>
<td>1.6</td>
<td>-0.4 - 0.7</td>
<td>ns</td>
</tr>
<tr>
<td>Depth of the tibial incisura, mm</td>
<td>0.1</td>
<td>0.7</td>
<td>-0.2 - 0.3</td>
<td>ns</td>
</tr>
<tr>
<td>Internal rotation of the talus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST, mm</td>
<td>-0.1</td>
<td>0.7</td>
<td>-0.3 - 0.2</td>
<td>ns</td>
</tr>
<tr>
<td>AW, of the incisura, mm</td>
<td>-0.6</td>
<td>0.9</td>
<td>-0.9 - 0.2</td>
<td>**</td>
</tr>
<tr>
<td>PW, of the incisura, mm</td>
<td>0.0</td>
<td>0.8</td>
<td>-0.3 - 0.2</td>
<td>ns</td>
</tr>
<tr>
<td>TFCS, mm</td>
<td>0.2</td>
<td>0.8</td>
<td>-0.1 - 0.5</td>
<td>ns</td>
</tr>
<tr>
<td>Rotation, degrees</td>
<td>0.9</td>
<td>4.0</td>
<td>-0.5 - 2.3</td>
<td>ns</td>
</tr>
<tr>
<td>Neutral position</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST, mm</td>
<td>0.5</td>
<td>0.9</td>
<td>0.2 - 0.9</td>
<td>**</td>
</tr>
<tr>
<td>AW, of the incisura, mm</td>
<td>-0.3</td>
<td>0.8</td>
<td>-0.6 - 0.0</td>
<td>ns</td>
</tr>
<tr>
<td>PW, of the incisura, mm</td>
<td>0.8</td>
<td>0.9</td>
<td>0.5 - 1.1</td>
<td>***</td>
</tr>
<tr>
<td>TFCS, mm</td>
<td>0.1</td>
<td>0.8</td>
<td>-0.2 - 0.4</td>
<td>ns</td>
</tr>
<tr>
<td>Rotation, degrees</td>
<td>0.5</td>
<td>3.8</td>
<td>-0.9 - 1.8</td>
<td>ns</td>
</tr>
<tr>
<td>External rotation of the talus</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ST, mm</td>
<td>0.1</td>
<td>0.9</td>
<td>-0.2 - 0.4</td>
<td>ns</td>
</tr>
<tr>
<td>AW, of the incisura, mm</td>
<td>-0.4</td>
<td>1.0</td>
<td>-0.8 - 0.1</td>
<td>ns</td>
</tr>
<tr>
<td>PW, of the incisura, mm</td>
<td>0.5</td>
<td>0.6</td>
<td>0.3 - 0.8</td>
<td>**</td>
</tr>
<tr>
<td>TFCS, mm</td>
<td>0.2</td>
<td>0.9</td>
<td>-0.1 - 0.6</td>
<td>ns</td>
</tr>
<tr>
<td>Rotation, degrees</td>
<td>1.2</td>
<td>3.4</td>
<td>-0.1 - 2.4</td>
<td>ns</td>
</tr>
</tbody>
</table>

<sup>1</sup> Significance from paired t-test, <sup>2</sup> ns = no significant difference, * = p < 0.05, ** = p < 0.01, *** = p < 0.001

5.4.2 Tibiotalar joint (III)

In the static measurements of the neutrally loaded tibiotalar joint (III), when comparing right and left ankle, minor intrasubject (i.e., bilateral) asymmetry was exhibited in the talar rotation. There was significant asymmetry in the talar rotation in internal rotation (mean difference 2.7 degrees, p = 0.006), in external rotation (mean difference 2.9 degrees, p = 0.006) and in the neutral position (mean difference 2.5 degrees, p = 0.006) (Table 10).

In the calculated dynamic measurements of the tibiotalar joint, there was no intrasubject (i.e., bilateral) asymmetry in the rotational dynamics of the tibiotalar joint (Table 11).
### Table 10. Asymmetry between ankles, WBCT measurements of the tibiotalar joint (III).

<table>
<thead>
<tr>
<th>Measurement, Right - Left</th>
<th>Mean Difference 95% CI of the Difference</th>
<th>p ^1,2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difference</td>
<td>SD</td>
</tr>
<tr>
<td>Internal rotation of the talus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>-2.7</td>
<td>3.4</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>AW, mm</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>PW, mm</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>0.1</td>
<td>2.2</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>-0.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Neutral position</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>-2.5</td>
<td>2.1</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>AW, mm</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>PW, mm</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>-0.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>External rotation of the talus</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>-2.9</td>
<td>3.9</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>-0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>AW, mm</td>
<td>-0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>PW, mm</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>-0.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>-0.4</td>
<td>1.5</td>
</tr>
</tbody>
</table>

1 Significance from paired t-test, ^2 ns = no significant difference, ^* = p < 0.05, ^** = p < 0.01, ^*** = p < 0.001

### Table 11. Asymmetry of the measurements in rotation of the talus, change between ankles.

<table>
<thead>
<tr>
<th>Measurement, Right - Left</th>
<th>Mean Difference 95% CI of the Difference</th>
<th>p ^1,2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difference</td>
<td>SD</td>
</tr>
<tr>
<td>External - Internal rotation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Talar Rotation, degrees</td>
<td>-0.2</td>
<td>4.6</td>
</tr>
<tr>
<td>MCS, mm</td>
<td>-0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>AW, mm</td>
<td>-0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>PW, mm</td>
<td>-0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>TrT, mm</td>
<td>-0.3</td>
<td>2.5</td>
</tr>
<tr>
<td>Talar tilt, degrees</td>
<td>0.1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

1 Significance from paired t-test, ^2 ns = no significant difference, ^* = p < 0.05, ^** = p < 0.01, ^*** = p < 0.001
5.5 The effect of sex and age

In NWBCT of the syndesmosis (I), differences between males and females were detected in PW, LI, and ST. Females had a smaller incisura length and narrower incisura posteriorly due to smaller joints. In WBCT of the syndesmosis (II), no significant differences were seen in the position of the fibula or the movement of the fibula between age groups, sexes or in respect of bilateral ankle (data not shown). Age and sex were not associated with asymmetry of dynamic measurements (data not shown). In WBCT of the tibiotalar joint (III), increasing age was associated only to talar tilt, as the talus was more everted in the external rotation position \( (p = 0.036, r = 0.342) \). Age or sex did not affect the measurements between positions and were not associated to asymmetry in dynamic measurements or to bilateral asymmetry (data not shown).

5.6 Inter- and intraobserver reproducibility (I, III)

In NWBCT of the syndesmosis (I), there was good to excellent inter- and intraobserver reliability in all measurements. ICC values were 0.73 for AW, 0.90 for PW, 0.61 for LI, 0.73 for DI, 0.93 for NI, and 0.92 for ST, and the kappa-values were 0.85 for NI and 0.80 for ST. The corresponding ICC values between two readings by one radiologist were 0.75 for AW, 0.97 for PW, 0.79 for LI, 0.97 for DI, 0.93 for NI, and 0.90 for ST, and the kappa values were 0.95 for NI and 0.80 for ST. In the WBCT study (II) the same measurement methods were used.

In WBCT of the tibiotalar joint (III), all the CT measurements demonstrated good to excellent inter- and intraobserver reliability. The ICC values for the interobserver reliabilities were 0.98 for talar rotation, 0.95 for MCS, 0.95 for AW, 0.98 for PW, 0.90 for AT, and 0.88 for talar tilt. For the intraobserver reliabilities, they were 0.98, 0.95, 0.95, 0.90 and 0.89, respectively.
6 Discussion

6.1 Findings

- This study demonstrates that in the axial CT imaging of the syndesmosis the fibula is located either anteriorly or centrally in the tibial incisura in 88–97% of patients in both the supine position with resting ankles and in the neutral standing position.
- When the ankle is rotated maximally, the fibula slides back and forth in the tibial incisura with a total movement of 1.5 mm and a rotation of 3°, with no significant lateral widening in the joint space.
- When the talus is rotated externally, the fibula moves to the posterior position in the tibial incisura in 40% of subjects. At the same time, the posterior width of the incisura is narrowed and the anterior width widened by concomitant external rotation of the fibula.
- When the talus is internally rotated, the fibula moves slightly anteriorly, and the posterior width of the incisura is increased, but the anterior width does not change significantly.
- When the ankle is rotated maximally, the talus rotates 10° in the ankle mortise, with no change in the MCS and no significant lateral widening in the joint space.
- The variation between the subjects is large in both supine, neutral, and rotational stress images, but when different ankles of the same subject were compared, there was very little or no intrasubject variation (less than 1 mm at all measurement points). This is also true for total rotational range of motion.

6.2 CT measurements

These studies provide a wide range of reference values to evaluate the normal anatomy of the syndesmosis and tibiotalar joint in both supine and weight-bearing cross-sectional imaging. They also demonstrate the dynamics of a normal ankle in order to redefine the rules of ankle rotational stability. The measurements of sagittal translation of the fibula in the syndesmosis have not been reported previously. The results of this thesis suggest that posterior translation is rare in normal populations, and in a postoperative imaging, it should be considered a potential sign of malreduction. Previous studies show that surgical fixation can cause malreduc-

The distal tibiofibular joint can be narrowed in some part of the joint, and based on clinical experience and the results of this thesis, the location of the narrowest part is arbitrary, although it is anterior in most cases. This has not been reported previously. In clinical postoperative imaging, malreduction of the syndesmosis can cause local posterior narrowing in the tibiofibular joint, and Study I demonstrated that it can also be seen in the normal population, although rarely.

In standard radiographs, injury of the syndesmosis can go undetected, and the accuracy of the reduction of the syndesmosis can be impossible to evaluate (Ebraheim et al. 1997, Marmor et al. 2011, Miller et al. 2009, Nielson et al. 2005, Pneumaticos et al. 2002, Takao et al. 2001). If evaluation is based on traditional radiographic criteria, it can even lead to unnecessary operative treatment (Harper & Keller 1989, Shah et al. 2012). The traditional criterion in CT measurements for malreduction of the syndesmosis has been a 2-mm difference between the anterior and posterior widths of the syndesmosis (PW-AW) (Burns et al. 1993, Gardner et al. 2006b, Harris & Fallat 2004, Teramoto et al. 2008). However, previous CT studies of the normal syndesmosis (Dikos et al. 2012, Ebraheim et al. 1997b, Elgafy et al. 2010, Gardner et al. 2006b, Mukhopadhyay et al. 2011) have suggested wider anatomical variation and questioned the parameters (Dikos et al. 2012, Miller et al. 2009, Mukhopadhyay et al. 2011), which is supported by the results of this thesis.

One limitation of the previous studies has been a lack of consensus on how to evaluate the congruence of the syndesmosis. The measurements were either projectional, or were not based on true distances (Dikos et al. 2012). They also did not use standardized measurement points (Gardner et al. 2006). Traditional radiography-based measurements are projectional and vary considerably with ankle rotation, and the same principle can lead to similar errors with CT measurements (Beumer & Swierstra 2003, Beumer et al. 2004, Pneumaticos et al. 2002). In studies I and II, projection-based measurements were not used to avoid any of these inaccuracies. All measurements from the syndesmosis and tibiotalar joint were true distance measurements with standardized measurement points demonstrating good to excellent intra- and interobserver correlations.
6.3 Dynamics

The WBCT studies II and III demonstrate the normal anatomy and dynamic motions of the weight-bearing distal tibiofibular and tibiotalar joints.

The findings of this thesis support the previous biomechanical cadaveric studies where only minimal fibular rotation and widening of the syndesmosis have been detected, but in external rotation of the ankle some posterior translation of the fibula is seen (Beumer et al. 2006, Close 1956, Katzenelson et al. 1983, Ogilvie-Harris et al. 1994, Sarsam & Hughes 1988, Teramoto et al. 2008). The rotational range of the talus was similar as in previous cadaveric studies, where the talus rotated 5–6° during rotation of the tibia or dorsiflexion of the ankle, respectively (Beumer et al. 2003, Close 1956, de Asla et al. 2006, Lundberg et al. 1989, McCullough & Burge 1980, Siegler et al. 2014). In the radiostereometric analysis of 11 patients with reconstructed lateral ligaments, Beumer et al. (2003) reported that external rotation moment of 7.5 Nm translated the talus 16° externally, 1.9 mm anteriorly, and 3 mm laterally while the patients were lying supine.

Study II demonstrated the normal rotation and sliding of the fibula in the incisura, which may be restricted by syndesmosis transfixation (Liu et al. 2013, Manjoo et al. 2010, Needleman et al. 1989, Peter et al. 1994). This may explain why syndesmotic screws have a tendency to fracture or loosen, probably due to normal movement in the distal tibiofibular joint (Bell & Wong 2006, Egol et al. 2004, Manjoo et al. 2010). It may also explain why clinical and functional outcomes are better if syndesmotic fixation screws are broken, loosened, or removed (Bell & Wong 2006, Manjoo et al. 2010, Miller et al. 2010, Needleman et al. 1989).

Study III also demonstrated in vivo the normal sliding, rotating, and tilting of the talus for the first time. In the tibiotalar joint, the largest range of motion was seen in rotation. The medial joint width measures changed only subtly, being the smallest in the MCS. This indicated how a healthy tibiotalar joint is a firmly stabilized structure (Ebraheim et al. 2006, Miller et al. 1995, Norkus & Floyd 2001, Rasmussen et al. 1982), and except for the talar rotation, only minor movements were witnessed. Even if the ankle joint cartilage had been shown to undergo progressive degenerative changes during aging, sex and age were not associated with any differences in respect to rotations (Muehleman et al. 2010).
6.4 Intersubject and intrasubject variation

These studies demonstrated large intersubject variation in both the static and dynamic measurements, but only minor intrasubject variation. Given this information, when assessing the anatomy of the syndesmosis and evaluating postoperative joint integrity, decisions should not be based solely on AW and PW measurements from one ankle with reference values obtained from population samples (Dikos et al. 2012, Mukhopadhyay et al. 2011). Because of significant intersubject variation, the patient’s contralateral ankle can and should be used as an individual roadmap.

The intersubject variations were larger in both incisural width measurements and in the posterior-anterior difference (PW-AW) than suggested by previous studies (Gardner et al. 2006). There appear to be some differences when genders are evaluated separately, since findings were clear in the male population, whereas in the female population, these results were in closer agreement with previous NWBCT findings (Gardner et al. 2006). In the current NWBCT study, significant differences were observed between females and males in LI, PW, and PW-AW. This suggests that joint size, and possibly gender, should be taken into account when diagnosing malreduction of the syndesmosis. In the WBCT of the syndesmosis, the variation was largest in the posterior part of the joint (PW) where the movement was most prominent. These findings underline that the larger joint size of males may lead to a false presumption of malreduction, especially if traditional measurement methods (PW-AW) are used. Females had significantly smaller sagittal translation distances, probably due to the smaller size of the joint, but there was no difference between the genders when fibular positioning in the incisural groove was assessed. There was also no difference in anterior incisural width, supporting the finding of studies I and II, where the fibula is normally positioned in either the anterior or central part of the incisura. A previous study (Murphy et al. 2014) demonstrated that the height of the subjects correlated with joint space widths in the upper ankle joint, but in this study, the subject’s height was not taken into account.

Even if most of the measurements were convergent, some minor asymmetry between ankles was present in the WBCT study of the syndesmosis and tibiotalar joint. In the syndesmosis, there was some minor asymmetry in ST and PW (0.5–0.8 mm). It may have resulted from a true anatomic variation, but it is also possible that due to asymmetry of the imaging equipment and armrests, the posture and rotation were not identically optimized on both sides. Athleticism might explain
asymmetry (Lin et al. 2013), when a dominant side may affect the minor asymmetry, but in a population with non-athletic backgrounds, the hypothesis does not get support (McGrath et al. 2015). It can also be speculated that such minor (less than 1 mm) differences are not clinically significant. Interestingly, in total rotational range of the talus, there was no asymmetry between ankles.

In determining the fibular positioning and syndesmosis reduction, the CT scan measurements were reproducible and were not affected by the gender of the subject or the size of the joint. Two of the previous studies (Elgafy et al. 2010, Mukhopadhyay et al. 2011) used a similar method to measure incisural width. But since tibial tubercles can be shallow and the medial border of the fibula spherical, defining the starting point of the measurement can be difficult, and the reproducibility of the measurements may hence be impaired. The standardized measurement points were introduced, and the results show that good intra- and interobserver reliabilities can be achieved.

6.5 Strengths and limitations

In Study I, the strength was the relatively large number of patients included. Also, there were patients from both sexes and different age groups. The results showed agreement with previous studies. The cross-sectional imaging with true distance measurements was used instead of projection-based measurements to avoid inaccuracies caused by incorrect positioning of the ankle for imaging or image reading. All measurements were standardized and demonstrated good to excellent intra- and interobserver correlations.

In Study II and Study III, the novel low dose WBCT system was used for physiological weight-bearing imaging. The imaging allows multiplanar reformations that precisely demonstrate the bony structures and standardized, reproducible measurements without distortion.

In Study II and Study III, healthy subjects with no history of trauma or malalignment were used. All the subjects were examined by an orthopedic surgeon before imaging. The variation of measurements in previous studies (Donken et al. 2013, Schoennagel et al. 2014) of talar rotation movement and joint widths suggest that the number of subjects is sufficient to draw conclusions of the outcome measures.

There are also several limitations. Study I included patients with pre-existing conditions such as malrotation of the lower limb, internally fixated femoral fractures, and miserable malalignment syndrome. Theoretically, even without preced-
ing ankle fracture or other significant injury, these conditions may have indirectly affected the ankles. However, the results did not support this, since there was no intrasubject variation between the intact and injured ankle. Furthermore, in Study I, patients’ medical records were used to evaluate previous medical history, and it is possible that some minor injuries (e.g. sprains) could have been missed. It was assumed that if there had been a clinically relevant sprain, it would have caused variation between ankles, but no bilateral variation was noted in this study. On the other hand, it can also be considered as a strength of this study that these patients were included, since possible anatomic variations due to underlying conditions did not affect the anterior fibular placement.

Study II and Study III had their limitations. Secondary outcome measures were of less importance, and to draw strong conclusions about the effects of age and sex on the dynamics, group comparisons were likely underpowered. Even if ankle positioning and all WBCT imaging was supervised by one of the researchers and the subjects were encouraged to rotate as much as possible, the rotational forces were not measured from all the subjects. Some of the bilateral variation in rotation and posture may be explained by this. Nonetheless, the previous biomechanical studies have yielded similar results (Beumer et al. 2003, Close 1956, Donken et al. 2013, Lundberg et al. 1989, McCullough & Burge 1980), suggesting that sufficient torque power was applied. Only rotations were measured, and not all the dimensions of ankle mobility were tested (dorsal and plantar flexion, and medial and lateral traction were not measured). Nevertheless, a previous biomechanical study (Beumer & Swierstra 2003) showed that compared to other movements, rotation causes the largest force in displacing the talus.

6.6 General considerations and future aspects

Previous studies show that both syndesmotic injury and inaccurately reduced syndesmotic can go undetected in standard radiographic imaging (Ebraheim et al. 1997, Marmor et al. 2011, Miller et al. 2009, Nielson et al. 2005, Pneumaticos et al. 2002, Takao et al. 2001). This has led to recommendations to use cross-sectional imaging intra- or postoperatively to define the findings correctly (Dikos et al. 2012, Elgafy et al. 2010, Franke et al. 2012, Gardner et al. 2006, Miller et al. 2009, Mukhopadhyay et al. 2011, Vascular et al. 2006, et al. Sagi 2012). Despite the slightly higher radiation dose (Biswa et al. 2009), the results of this thesis suggest the use of CT over radiography. Since the intrasubject variation between the ankles is not significant, scanning both ankles is recommended. Es-
pecially if future operative treatment is planned, the other ankle can and should be used as a reference and roadmap. In imaging of the syndesmosis, using standardized measurement points and true cross-sectional measurements is recommended to avoid rotational malpositioning and to reduce false positive or negative findings.

These new in vivo tools with standardized measurement methods and knowledge of normal cross-sectional anatomy might help us to study instability and its role in prolonged symptoms and long-term complications after ankle injury.

For the proper functioning of the ankle, rotational stability of the talus and syndesmosis are necessary. These rotational problems have been difficult to detect in 2D radiographs. CT imaging shows accurately the internal derangements of the joints, and current reference values help to correctly evaluate rotational problems in order to redefine the rules of rotational stability. The bilateral stress WBCT scans are a promising tool for the further investigation of patients with rotational instability (acute or previous ankle injury). Even the effect of conservative treatment of ligamentous injuries can be measured. Also, both reduction and stability of the fixed syndesmosis can be evaluated.

Further prospective studies of different types of injuries are needed to understand the correlation of syndesmosis changes and increased talar rotation with functional outcome in long-term results. In the future, WBCT may help clinicians to understand conditions causing prolonged healing after ankle injury. The relationship between the severity of the ankle injury and the degree of instability can also be measured as a possible factor leading to post-traumatic problems, such as late ankle instability and osteoarthritis.
7 Summary and conclusion

I These studies introduce a standardized, reproducible measurement method to evaluate the distal tibiofibular syndesmosis. The data also demonstrate that in the normal population, the fibula is located either centrally or anteriorly in the incisura of the tibia in a supine CT. If there is posterior translation of the fibula in the postoperative imaging, malreduction should be considered. The intersubject variation is large, but the intrasubject variation between ankles is minor, which suggests that the contralateral ankle should be used as a reference when evaluating possible malreduction.

II Additionally, in the upright weight-bearing position, the fibula is situated anteriorly in the tibial incisura in a majority of patients. When the ankle is rotated, the distal tibiofibular joint is not widened, even if the fibula rotates and slides anteriorly and posteriorly in the incisura. Also, in the upright position, large intersubject variation is detected, whereas the intrasubject variation between ankles is only minor. This suggests that the contralateral ankle should be used as a reference in examinations involving the malreduction of the syndesmosis, as well as in studies on the dynamics of the distal tibiofibular joint.

III A standardized, reproducible measurement method to evaluate the tibiotalar joint in cross-sectional imaging is introduced. When the lower leg is rotated in the upright weight-bearing position, the talus rotates 10° with no medial clear space widening. Sex and age do not affect most of the measurements; only a minor tilting of the talus was seen in the older population in maximal external rotation. Furthermore, at the level of the tibiotalar joint, there is a large intersubject variation, but only minor intrasubject variation between ankles. This suggests that the contralateral ankle should be used as a reference when malreduction of the syndesmosis or tibiotalar joint instability is suspected.
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