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The influence of ankle ligament rupture and operative repair on kinematics during gait

door Nette D'Haene

masterproef aangeboden, tot het behalen van de graad van Master of Science in de revalidatiewetenschappen en kinesitherapie

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WOORD VOORAF

Allereerst wil ik gebruik maken van dit voorwoord om prof. Ilse Jonkers te bedanken, voor de kans die ik heb gekregen te werken aan deze thesis. Dankzij haar kon ik 2 jaar lang werken aan een project dat ik oprecht heel interessant vond. De flexibiliteit en autonomiteit die ik kreeg, samen met de accurate en motiverende feedback, zorgden voor een leuke drive doorheen het proces. Daarnaast wil ik drs. Hannelore Boey enorm bedanken, voor de dagdagelijkse begeleiding. Bij Hannelore kon ik op elk moment terecht, van de kleinste detailvragen tot momenten waar ik vastzat en niet meer wist hoe ik het verder moest aanpakken; voor elk probleem leek Hannelore een oplossing klaar te hebben. Ik kan me, zonder een vleier te willen zijn, geen betere co-promotor voorstellen. Ook Dr. Verfaillie wil ik graag bedanken voor zijn chirurgische expertise tijdens de experimenten.

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SITUERING

De masterproef is gekaderd binnen de projecten van de onderzoeksgroepen *Human Movement Biomechanics Group*, gesitueerd binnen de Faculteit Bewegings en Revalidatiewetenschappen en de *Biomechanics Section* gesitueerd in de afdeling Mechanical Engeneering.

Binnen de Human Movement Biomechanics Group staat de mechanica van het muskuloskeletale systeem tijdens motorische functies centraal. Een van de voornaamste onderzoeksdoelen is om causale relaties te kunnen beschrijven tussen de veranderingen binnen het muskuloskeletaal systeem en opgelegde mechanische of neurofysiologische beperkingen. In dit werk werd de voet- en enkel-kinematica bestudeerd en werden beïnvloedende effecten van verschillende ligamentaire condities op deze kinematica geëvalueerd. Daarnaast werd ook de invloed van een gesimuleerd inversietrauma op de kinematica nagegaan.

Binnen de Biomechanics Section wordt het onderzoekstopic opgedeeld in 4 clusters, ondermeer 'mechanica van zachte weefsels', waar onderzoekers werken rond herstel en regeneratie van zachte weefsels. Het interesseveld van deze studie rond ligamentruptuur en reconstructie met overbrugging van de InternalBrace past binnen dit onderzoeksdomein. Ook het gehanteerde protocol, waarbij een in vitro set-up met kadavers werd gewerkt, past binnen de Biomechanics Section. De kadaver-voeten doorliepen een experimenteel protocol, waarbij ze onder verschillende ligamentaire condities de steunfase van de gangcyclus doormaakten.

Enkeldistorties zijn vaak voorkomende letsels in de maatschappij, zeker tijdens fysieke activiteit en sportgebeuren. Het grootste deel van de enkeldistorties, tot 85%, is het gevolg van een inversietrauma, waardoor laterale ligamenten beschadigd kunnen raken. [5] Bij het grootste deel van de patiënten met ligamentaire schade, is het anterior talofibulair ligament (ATFL) beschadigd [1], in sommige gevallen ook het calcaneofibulair ligament (CFL).[1] De eerstelijnsaanpak na ligamentruptuur van de enkel is in de meeste gevallen conservatief, met de opstart van kinesitherapie. In 20 tot 25% van de gevallen is dit onvoldoende, waardoor enkeldistorties blijven optreden en patiënten klagen over aanhoudende pijn en gevoel van instabiliteit.[4] Bovendien heeft onderzoek de relatie aangetoond tussen chronische enkel instabiliteit en degeneratieve veranderingen in het enkelgewricht, waaronder chondrale aandoeningen en artritis. Een operatieve ingreep kan aangewezen zijn in gevallen van chronische instabiliteit. [2, 4]

De afgelopen decennia werden verschillende technieken ontwikkeld en geëvalueerd, om operatieve ingrepen in dit vak zo goed mogelijk te optimaliseren en een gepaste alternatieven te vinden voor bestaande limitaties. [3, 4]

Referenties

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ABSTRACT

Background: Despite good clinical outcomes of the Brostrøm procedure for secondary repair of chronic lateral ankle instability, the reported inferior strength of the repaired ligament might result in persisting instability and pain. Augmenting of the repaired ligament with a suture tape improves the construct strength, but no biomechanical studies investigated the effect on the joint movement.

Purpose: To document the effect of an isolated ATFL vs combined ATFL and CFL ligament rupture and the effect of an isolated vs combined ligament reconstruction with augmentation of the InternalBrace, on gait kinematics of the foot and ankle. The second purpose is to document the effect of a simulated lateral ankle sprain on the gait kinematics by the use of a trapdoor, for all the conditions.

Study Design: Descriptive Laboratory Study

Methods: Five fresh-frozen cadaveric ankles were prepared and mounted to a cadaveric gait simulator. All the specimens experienced five different conditions: intact ligament state, ruptured ATFL, ruptured ATFL and CFL, reconstruction with augmentation of ATFL and CFL, reconstruction with augmentation of ATFL. 3D biomechanical analysis was performed to calculate the range of motion and average angle for the different hindfoot and midfoot joints, for all the conditions.

Results: A ruptured ATFL affected the talorural, talonavicular, subtalar and tibiocalcaneal joint for various planes. A combined rupture of ATFL and CFL affected the talocrural, subtalar and calcaneocuboid joint in various planes. A reconstruction of ATFL with augmentation of the InternalBrace restored some of the observed deviations, caused by the ligament rupture in the subtalar joint. A combined ATFL and CFL reconstruction with augmentation of the InternalBrace restored some of the observed deviations, caused by ligament rupture, for the talocrural, subtalar and talonavicular joint. The α-level was set at 0,05.

Conclusion: The ATFL and CFL contribute to the stability of multiple joints in the foot, since the influence of an isolated ATFL and combined ATFL-CFL rupture is not restricted to respectively the talocrural and subtalar joints, but also affect the midfoot joints. A combined ligament reconstruction of ATFL and CFL with augmentation of the IB mainly restores the frontal plane instability for the talocrural joint.

Clinical Relevance: The present Broström-Gould procedure might be insufficient for patients with persisting CAI after a conservative approach, due to the inferior strength compared to the uninjured ligament. Previous studies already revealed that augmentation of the ligament repair with a suture tape, can increase the potency of the construct. This work showed that a combined augmented reconstruction of the ATFL and CFL, restores the talocrural instability in the frontal plane, where inversion-eversion movements occur.

Key Terms: anterior talofibular ligament (ATFL), calcaneofibular ligament (CFL), lateral ankle ligament rupture, gait simulation

INTRODUCTION

Three main factors contribute to ankle stability: the intrinsic and extrinsic muscles (who contribute to the dynamic stability), the articular construction and geometry of the ankle joint (where the congruency accounts for stability when the joint is loaded) and the ankle ligaments. [4] When one or more of these factors are compromised, the stability can be reduced and ankle sprains can occur.

Ankle sprains are one of the most common injuries in sports, accounting for 15-20% of all injuries. [4, 28] A hyperdorsiflexion trauma might typically cause an injury to the distal tibiofibular or syndesmotic ligaments, an eversion trauma can imply damage to the medial structures (the deltoid ligaments). However, most of the ankle sprains - approximately 85%- are a result of inversion traumas, damaging the lateral structures. [7, 28].

The anterior talofibular ligament (ATFL) is the most frequently injured ligament, in 65% of the patients. [10, 20] Running horizontally from the fibular tip to the talar body, the ATFL limits anterior displacement of the talus and plantar flexion of the ankle. During plantar flexion, the ligament is under strain and becomes vulnerable for injury, especially when combined with a supination movement. [4] In 20 % of the patients, there is a combined rupture of the ATFL and the calcaneofibular ligament (CFL). [2, 20] The CFL originates just below the fibular insertion of the ATFL, and runs obliquely downwards and backwards to the calcaneus. The CFL is the only ligament that extends across both the talocrural and the subtalar joint, playing a role in subtalar stability. [23] The posterior talofibular ligament is usually not injured, unless there is a major trauma with frank dislocation of the ankle. [7]

When ligament injury is confirmed by clinical examination and/or imaging, the first line approach is always conservative. Physiotherapy is followed for at least three months to improve the lateral ankle instability. [23] However, 20 to 25% of patients fail to respond to physiotherapy and have continuing symptoms of instability and pain. [29] Lasting chronical ankle instability can alter ankle kinematics, resulting in suboptimal biomechanical loads and this can secondary lead to chondral injuries and ankle arthritis. [7, 23]., When ankle stability cannot be restored with non-surgical treatment, surgical intervention may be necessary. [28] Anatomical procedures are preferred above non-anatomical ones as they are associated with more optimally restored anatomy, less complications (such as wound healing or nerve problems), easier surgical techniques, but also better post-operative mobility. [3] In 1966, Broström described the first anatomical procedure, with direct ligament repair and preservation of the tendons.[2] Many variations to this procedure emerged, such as the Brostrom-Gould modification with incorporation of the inferior extensor retinaculum. [8, 23] This method is at the moment the golden standard to treat chronic lateral instability in clinics. [29] Despite high satisfaction rates, good clinical results and few complications, limitations of this technique emerge. Research showed that the current ligament restorations are much weaker than the uninjured ATFL and might not be strong enough to avoid sprain recurrence during physical activity. [28, 29] Therefore, early post-operative protection of the ATFL repairs is required, resulting in a long immobilization and rehabilitation period. [11] In addition, it is questionable if this anatomic repair technique is sufficient for patients with poor residual ATFL tissue, with more generalized laxity or for elite athletes. [21, 32].

As a consequence, new techniques have been developed. One of them is the InternalBrace by Arthrex.. [19, 28]. This technique augments the Broström repair with extra structural support. A strong non-absorbable wire is attached to a screw construct in the fibula and the talus. The InternalBrace has been a subject of investment over the last years, with different comparative studies and interesting outcomes in literature. In vivo studies used AOFAS scores (the American Orthopaedic Foot & Ankle Society), self-reported ankle stability and the anterior drawer and talar tilt test to evaluate the outcome of the surgery. [32] Other studies investigated the load to failure of the intact ligaments and the internal brace. [22, 28, 30] These studies already revealed the superior strength of reconstructions with augmentation of the Internal Brace in comparison to the healthy ligament and the classical Brostrøm-Gould procedure. [28, 30] This may reduce the need for early protection and make earlier rehabilitation possible. However, to our knowledge, all studies investigating the influence of the internal brace on the foot biomechanics involved quasi-static, non-weight bearing set-ups, while an inversion trauma is a dynamic weight bearing event. Therefore, there is a need for an objective evaluation on the influence of the internal brace on e.g. gait kinematics. In addition, there is no evidence if a combined ATFL and CFL augmentation has a better outcome than an isolated ATFL augmentation. Furthermore, the performance of the InternalBrace during an actual inversion trauma has not been tested yet.

Based on the previous findings, the purpose of this study is twofold: (1) firstly to document the effect of an isolated (ATFL only) vs combined (ATFL and CFL) ligament rupture and the effect of an isolated vs combined ligament reconstruction with augmentation of the InternalBrace on gait kinematics of the foot and ankle complex, compared to the intact condition. A cadaveric set-up is imperative for investigation of foot and ankle kinematics, since not all bony structures of the foot and ankle are accessible for measurements in vivo. Furthermore is this set-up more appropriate for mutual comparison of the different conditions for a particular specimen. The second purpose is (2) to document the effect of a simulated lateral ankle sprain on the gait kinematics by the use of a trapdoor, for all the conditions.

METHODS

Five fresh-frozen cadaveric ankles were used. The cadavers were amputated mid-tibially and were prepared by removing soft tissue from the proximal part of the lower leg (approximately 10 cm above the malleoli). The tendons of 10 major lower limb muscles were prepared by removing the muscles-bellies (m. peroneus longus, m. peroneus brevis, m. tibialis anterior, m. tibialis posterior, m. extensor digitorum, m. extensor hallucis, m. flexor digitorum, m. flexor hallucis, m. gastrocnemius, m. soleus).

The cadavers specimens were then mounted to a gait simulator (*Figure 1)*. By controlling the tibial kinematics, applying forces to the muscles tendons and providing representative ground reaction forces, the stance phase of gait can be simulated. This set-up has been previously validated and described in literature. [19]

Every cadaver is tested in five different conditions for two different measurements. The five conditions were: intact ligaments, an ATFL resection, an ATFL and CFL resection, reconstruction of ATFL and CFL and reconstruction of ATFL with resection of the CFL reconstruction. An experienced orthopaedic surgeon performed all the resections and surgeries. Standard instrumentation and techniques, representative of the clinical setting, were used. Both the ATFL and the CFL were augmented with the InternalBrace that uses the BioComposite Swivelock® and FiberTape® (Arthrex Inc, United States).

The two different measurements were normal over ground walking and walking with a forced inversion of 15° (compared to flat surface), caused by a trapdoor (*Figure 2)*. The use of the trapdoor to simulate ankle sprains is described in a study by Nieuwenhuijzen et al. [18]

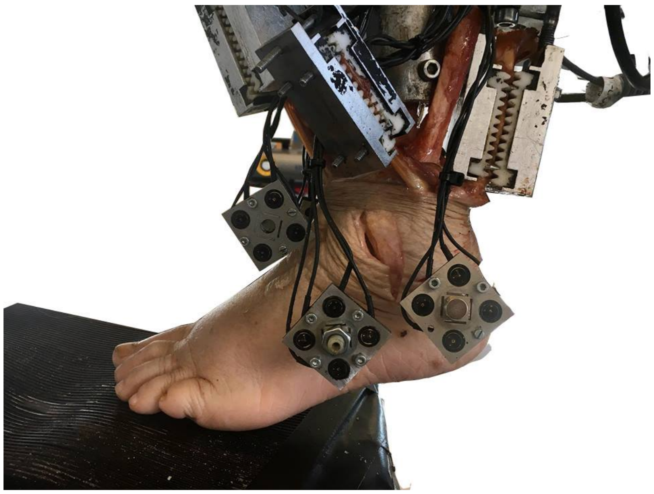


Figure 1: This figure shows the positioning of the clamps on the tendons and the bone pins to measure kinematics.

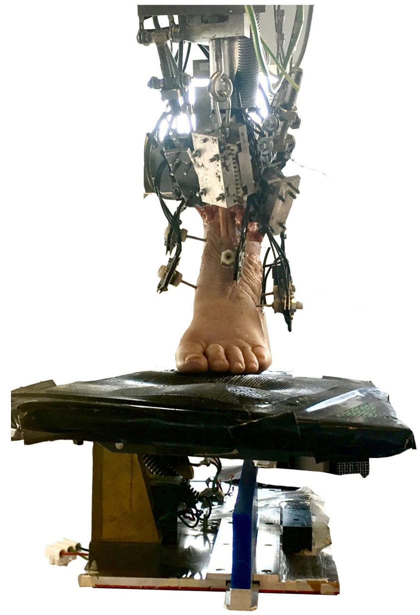


Figure 2: a trapdoor mechanism was used to simulate a lateral ankle sprain..

Hindfoot kinematics were measured during the stance phase of gait with a 3D motion capture system (Krypton K 600, Metris, Belgium). A bone pin was inserted in the tibia, talus, calcaneus, cuboid and navicular. On each pin, a cluster with four leds was positioned. The led position in combination with CT-based information on the bone pin position allows calculating 3D hindfoot angles between the different bones. Inversion-eversion was defined as the movement in the frontal plane (around the anterior-posterior axis), internal-external rotation as the movement in the transversal plane (around the proximal-distal axis) and dorsiflexion-plantar flexion as the movement in the sagittal plane (around the medial-lateral axis).

Based on the measured 3D hindfoot angles, the range of motion (ROM) and average angle (AA) were calculated for different articulations: talocruraral joint (tibia-talus), subtalar joint (talus-calcaneus), tibia-calcaneus (representing the hindfoot), talonavicular joint and calcaneocuboid joint. These values were calculated for all the conditions, in three movement directions: inversion-eversion, internal-external rotation and dorsiflexion-plantar flexion. By the use of the ROM, potential excessive or restricted mobility caused by ligament rupture or reconstruction, was explored. A shift in average angle indicated a global deviant position for a certain joint due to ligament rupture or ligament reconstruction.

Statistical analysis was performed in matlab (The MathWorks Inc, United States). A general linear mixed model was fitted to the data to study the effect of the different conditions and measurements on the ROM and AA in the five joints during the three movement directions. 427 trials were implemented in the analysis and the α-level was set at 0,05.

RESULTS

For normal over ground walking, data for every condition were compared with the intact ligament values (controls). Differences in ROM between controls and the various conditions were then calculated and plotted (Figure 3-5). Standard deviations were calculated for the intact condition to explore the variation in all control trials. A statistically significant difference was only considered as relevant if the absolute value of the difference with intact fell outside the standard deviation interval. Otherwise, the deviation could be explained by the variance of intact trials in normal walking. Similar procedure was applied to evaluate the relevance of the statistically significant differences for outcomes of the average angles.

Results for ROM

An isolated ATFL rupture resulted in an increased ROM in the frontal plane in the talocrural and talonavicular joint ($p<0,01$), in an increased ROM in the transversal plane in the subtalar joint ($p<0,01$) and in a decreased ROM in the sagittal plane in the talocrural and tibiocalcaneal joint ($p<0,01$). There were no significant differences between intact and an isolated ATFL rupture for the ROM in the other joints.

A combined ATFL and CFL rupture resulted in an increased ROM in the frontal plane for the talocrural joint ($p<0,01$) and the subtalar joint ($p<0,01$), in an increased ROM in the transversal plane for the subtalar joint ($p<0,01$), in an increased ROM in the sagittal plane for the calcaneocuboid joint ($p<0,01$) and in a decreased ROM in the sagittal plane for the talocrural joint ($p<0,01$). There were no significant differences found between intact and the combined rupture of ATFL and CFL for the ROM in the other joints.

A reconstruction with augmentation of the InternalBrace for ATFL and CFL, resulted in an increased ROM for the subtalar joint in both the frontal and the transversal plane ($p<0,01$), in a decreased ROM for the talocrural joint for both the transversal and sagittal plane (respectively $p<0.04$ and $p<0,01$) and in an increased ROM for the calcaneocuboid joint in the sagittal plane ($p<0,01$). There were no significant differences between intact condition and reconstruction of ATFL and CFL with augmentation of the InternalBrace for ROM in the other joints.

A reconstruction with InternalBrace augmentation of only the ATFL resulted in an increased ROM for the talocrural and subtalar joint in the frontal plane ($p<0,01$), in an increased ROM for the subtalar and calcaneocuboid joint in the transversal plane ($p<0{,}01$), in an increased ROM for the calcaneocuboid joint in the sagittal plane ($p<0{,}01$) and in a decreased ROM for the talocrural and tibiocalcaneal joint in the sagittal plane ($p<0{,}01$). There were no significant differences between intact condition and reconstruction of the ATFL with augmentation of IB for ROM in the other joints.

Results for Average Angle

A ruptured ATFL resulted in a shift in average angle towards increased external rotation for the talocrural joint ($p<0{,}01$), the subtalar joint ($p<0{,}02$) and the talonavicular joint ($p<0{,}04$), and a shift towards increased dorsi flexion for the talocrural joint ($p<0{,}01$), the tibiocalcaneal joint ($p<0{,}01$) and the talonavicular joint ($p<0{,}01$). It also resulted in a shift in AA towards increased plantar flexion for the calcaneocuboid joint ($p<0{,}04$). There were no significant changes in average angle between the intact condition and ATFL rupture for the other joints.

A combined rupture of ATFL and CFL resulted in a shift in AA towards increased inversion for the subtalar joint ($p<0{,}05$), increased eversion for the talocrural joint ($p<0{,}01$) and talonavicular joint ($p<0{,}01$) and a shift towards increased dorsiflexion for the talocrural joint. There were no significant changes in average angle between the intact condition and combined rupture of ATFL and CFL for the other joints.

A reconstruction with augmentation of the InternalBrace for ATFL and CFL, resulted in a shift in AA towards increased inversion for the calcaneocuboid joint ($p<0{,}01$), towards increased eversion for the tibiocalcaneal joint ($p<0{,}04$) and talonavicular joint ($p<0{,}01$), and a shift towards increased dorsi flexion for the talocrural joint (p<0,01), subtalar joint (p<0,02) and calcaneocuboid joint (p<0,04). There were no significant changes in average angle between the intact condition and reconstruction of ATFL and CFL with augmentation of the IB for the other joints.

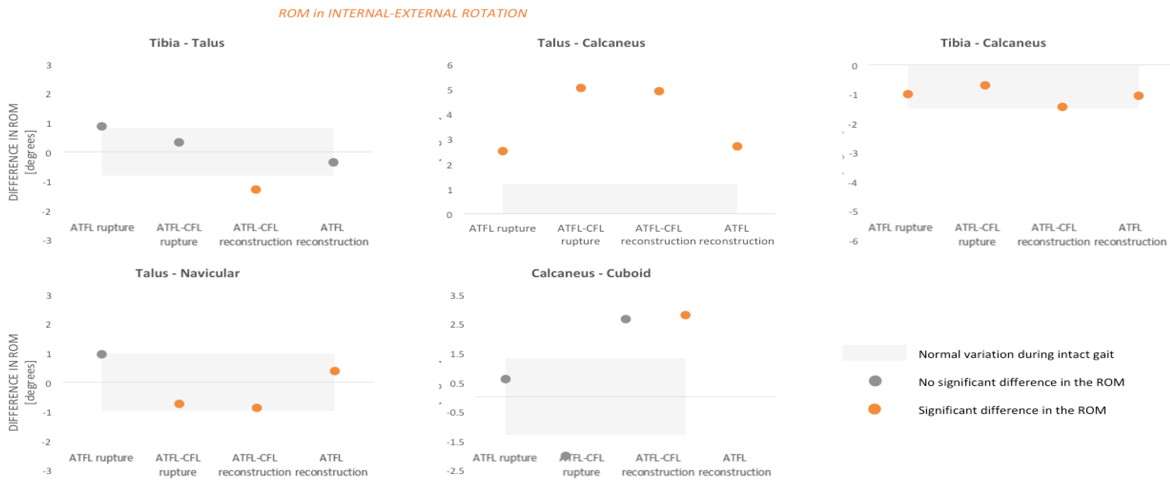
A reconstruction with InternalBrace augmentation of only the ATFL resulted in a shift in AA towards increased inversion for the subtalar joint (p<0,05) and calcaneocuboid joint (p<0,01), towards increased eversion for the talocrural joint (p<0,01), towards increased external rotation for the subtalar joint (p<0,02) and tibiocalcaneal joint (p<0,01). It also resulted in a shift in AA towards increased dorsi flexion for the talocrural (p<0,01) and subtalar joint (p<0,02) and finally a shift in AA towards increased plantar flexion for the talonavicular joint (p<0,01).

Pane A

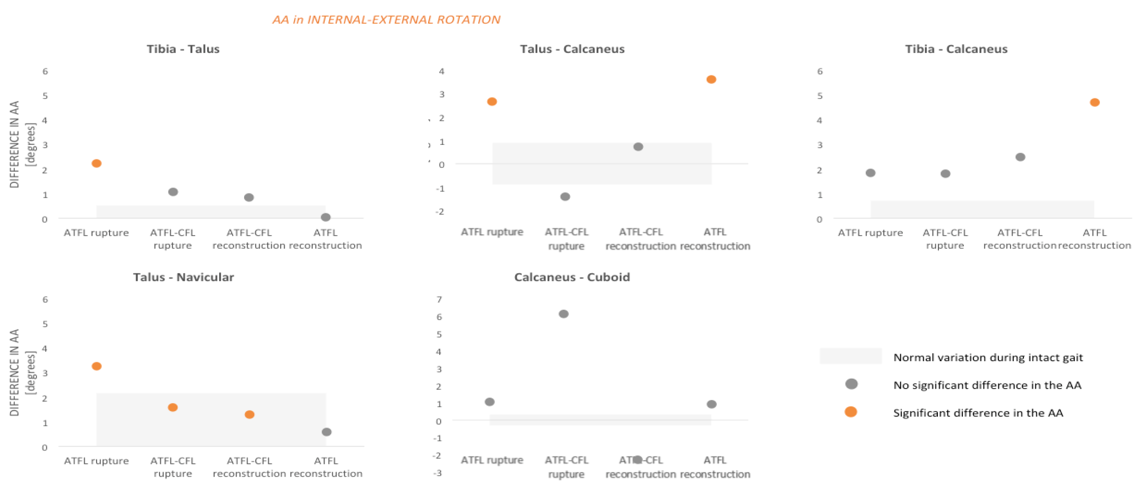
Pane B

Figure 3: The mean differences in frontal plane ROM (pane A) and AA (pane B) between intact and the various conditions were calculated and plotted, embodied by the dots. The statistically significant outcomes are marked by an orange dot; insignificant outcomes are marked blue. The grey zone represents the standard deviation of all intact trial ROM's (A) and AA's (B) in the frontal plane.

Pane A: a positive value indicates an increase in ROM, a negative value indicates a decrease in ROM. Pane B: a positive value indicates a shift in AA towards eversion; a negative value indicates a shift in AA towards inversion.

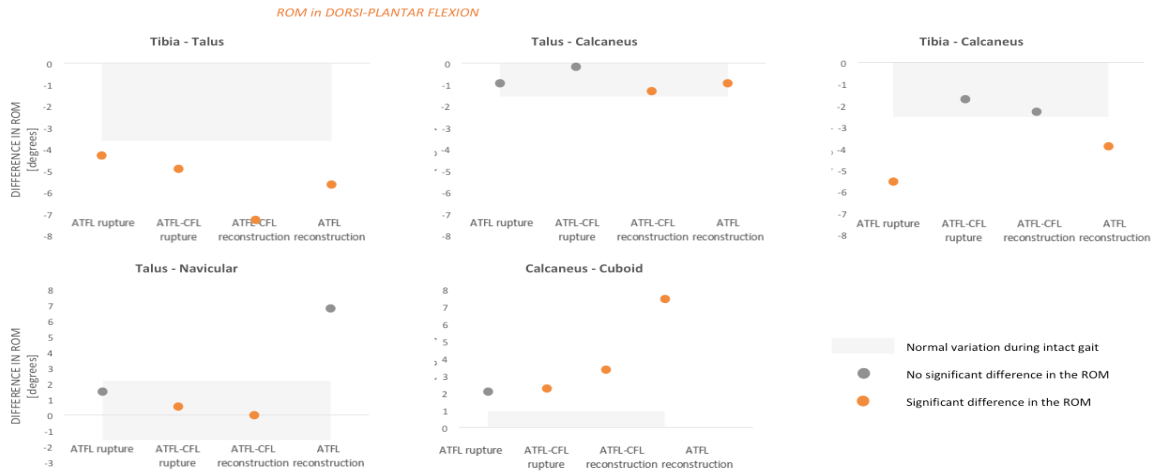


Pane A



Pane B

Figure 4: The mean differences in transversal plane ROM (pane A) and AA (pane B) between intact and the various conditions were calculated and plotted, embodied by the dots. The statistically significant outcomes are marked by an orange dot; insignificant outcomes are marked blue. The grey zone represents the standard deviation of all intact trial ROM's (A) and AA's (B) in the transversal plane. Pane A: a positive value indicates an increase in ROM, a negative value indicates a decrease in ROM. Pane B: a positive value indicates a shift in AA towards external rotation; a negative value indicates a shift in AA towards internal rotation.



Pane A

Pane B

Figure 5: The mean differences in sagittal; plane ROM (pane A) and AA (pane B) between intact and the various conditions were calculated and plotted, embodied by the dots. The statistically significant outcomes are marked by an orange dot; insignificant outcomes are marked blue. The grey zone represents the standard deviation of all intact trial ROM's (A) and AA's (B) in the sagittal plane.

Pane A: a positive value indicates an increase in ROM, a negative value indicates a decrease in ROM.

Pane B: a positive value indicates a shift in AA towards plantar flexion; a negative value indicates a shift in AA towards dorsiflexion.

Effect of trapdoor

For every joint, data of all conditions for stance phase of gait (normal walking) were compared with data of all conditions for the simulated ankle sprain with the use of a trapdoor (*figure 6)*. For ROM, significant difference was found in the sagittal plane, where a decreased ROM was reported for the talocrural and tibiocalcaneal joint, and an increased ROM for the talonavicular joint. No differences in ROM were found for the frontal and transversal plane in any of the joints. For the average angle, a shift towards external rotation was found for the talocrural and the tibiacalcaneus joint, and a shift in AA towards dorsiflexion for the calcaneocuboid joint. No differences were found in the frontal plane for any of the joints.

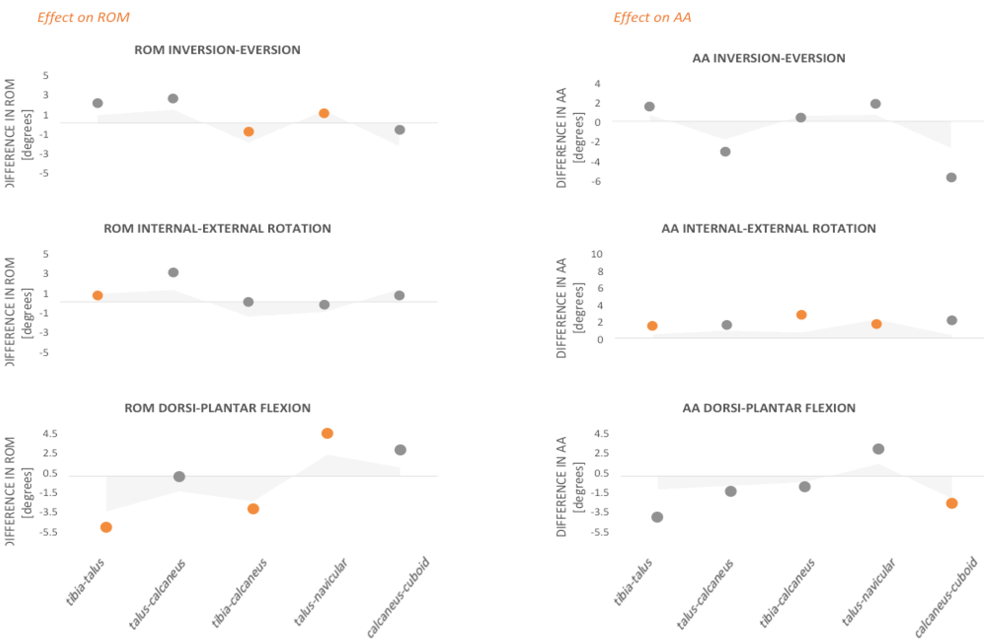


Figure 6: For every joint, differences in ROM (left) and average angle (right) between normal walking and the simulated lateral ankle sprain were calculated for all trials. For every joint, the standard deviation of all trials for normal walking was determined to explore the variance for normal walking trials. The dots represent the differences in ROM and AA: orange dots indicate statistically significant deviations between normal walking and simulated sprain; deviations marked by blue dots were not significantly different.

DISCUSSION

Although a conservative approach leads to good clinical outcomes for many patients with lateral ligament ankle sprains, a significant number of patients fails to respond to physiotherapy and has continuing symptoms of instability and pain. In addition, literature reported a relationship between chronic ankle instability and degenerative changes. Therefore, surgical intervention might be indicated in some cases. The InternalBrace by Arthrex augments the repaired ligament and has been a subject of investment over the last years. Previous studies indicated superior strength of reconstructions with augmentation of the Internal Brace, but to our knowledge, no previous studies investigated the effect of the InternalBrace on gait kinematics. In this study, the ROMs and average angles during the stance phase of gait were calculated for five different joints. Additionally, the effect of a simulated lateral ankle sprain on these gait kinematics was evaluated by the use of a trapdoor.

The calculated ROM values for the intact foot –our baseline– show acceptable correspondence to in vivo and in vitro kinematics described in literature [19, 31] for the talocrural, subtalar and tibiacalcaneal joint. This confirms that the simulation of gait is comparable to in vivo kinematics and can be used to evaluate the ROM and AA during the five different conditions. The talonavicucular and calcaneocuboid joints show some larger deviations compared to in vivo kinematics in the sagittal plane. The average angles during stance phase of walking were to our knowledge not reported in previous studies, by which our values could not be compared with previous findings.

Based on the location and orientation of the ATFL and CFL, it is expected that an ATFL rupture would influence mainly the talocrural joint and that an additional CFL rupture influences the subtalar joint too. [7, 23] The results of this study showed an increased ROM in the frontal plane in the talocrural joint with an ATFL rupture. When the CFL is impaired, the increased frontal plane ROM in the talocrural joint is even more pronounced. In addition, an increased frontal plane ROM in the subtalar joint was ascertained, what can be clarified by the location and orientation of the CFL, the only ligament that runs across the subtalar joint. The shift in average angle towards inversion indicates a more inverted position in general for the subtalar joint. Besides the frontal plane, the ROM in the transversal plane was also affected. For the subtalar joint, an ATFL rupture resulted in an increased transversal plane ROM and an more pronounced increase in transversal plane ROM when there is a combined rupture of ATFL and CFL. A shift in average angle towards external rotation for both talocrural and subtalar joint when the ATFL is ruptured suggests a change in the dynamic alignment of the ankle towards a more externally rotated position. These findings confirm the involvement of the ATFL in the talocrural stability, mainly in the frontal plane, and the involvement of the CFL in the subtalar stability, in both the frontal and transversal plane. These findings also indicate a partial engagement of the AFTL in the subtalar stability in the transversal plane, and impairment of the CFL amplifies the frontal plane instability caused by rupture of the ATFL in the talocrural joint.

For the talonavicular joint, an ATFL rupture resulted in an increased frontal plane ROM, also indicating an increased inversion-eversion movement in the midfoot. In the sagittal plane, results of this study showed a decreased ROM for the talocrural joint and the tibiocalcaneal joint (hindfoot) with a ruptured ATFL. The shift in average anlge towards dorsiflexion indicates a more dorsiflexed position for these joints in general. Previous studies investigating the biomechanical properties of patients with chronicle ankle instability (CAI), showed increased hindfoot, ankle and forefoot inversion (movement in the frontal plane) and a more externally rotated shank (movement in the transversal plane). [14, 17] . Furthermore, limited sagittal plane displacements were described in the study of Liu et al [14]. The overall consensus of the different studies reported in the systematic review of Liu, stated that patients with CAI have an increase of frontal plane displacement and limited sagittal plane motion. These kinematic observations for patients with CAI match with the findings in our cadaveric study for ligament rupture, however only particularly for the frontal and sagittal plane. The deviations in the transversal plane reported in this work, cannot be directly linked to in vivo findings in literature. However, the transversal plane deviations in this study are mainly reported in the subtalar joint, while in vivo studies cannot isolate movements in this joint since the talus is inaccessible for in vivo measurements of kinematics. This might be an explanation for the gap between our findings and the findings in literature.

The differences found in the talonavicular and the calcaneocuboid joint for isolated ATFL rupture or combined ATFL-CFL rupture, imply the influence of these ligaments on movements of the midfoot. Although the ATFL does not cross the talonavicular joint, a rupture results in an increased frontal plane ROM. [7] This might be explained by the insertion of the ATFL on the talus bone, partial responsible for the lateral stability. When the CFL is impaired as well, the calcaneocuboid joint shows an increased sagittal plane ROM, resulting from the lack of stabilization of the calcaneus by the CFL. These findings highlight the value of the multi-articular evaluation in this study and suggest a lack of information in clinical studies. The anterior drawer and talar tilt test, frequently described in in vivo and in vitro studies, only describes the effect of ligament ruptures and interventions for respectively the talocrural and subtalar joint, in respectively the sagittal and frontal plane.

[22, 28,] (Drakos et al., Waldrop et al.,. In the set-up used in this study, the effect of ATFL and CFL ligament rupture and reconstruction on the midfoot could be evaluated and showed important deviations. With this new insight, the prevalence of degenerative changes in the foot for patients with chronic ankle instability can be better comprehended. The excessive mobility caused by the impaired ligament(s), is not restricted to the underlying joint, but affects multiple joints. This increased generalized instability in the entire foot and ankle complex can damage different structures and in this way lead to degenerative changes. [27]

A ligament reconstruction aims to restore the instability caused by the impaired ligament(s). Results of this study showed that the combined ligament reconstruction of ATFL and CFL with augmentation of the InternalBrace was able to restore the increased frontal plane ROM for the talocrural joint, as well as the shift in average angle towards eversion. These results indicate the potential value of the InternalBrace to correct the inversion instability for patients with CAI. Based on the outcome of this study, a reconstruction of only ATFL seems insufficient to overcome the frontal plane instability in the talocrural joint. For the subatalar joint, none of the reconstructions could restore the increased frontal plane ROM. The shift in average angle towards inversion caused by rupture of ATFL and CFL was restored by augmented reconstruction of both ligaments. The reported transversal plane deviations in the subtalar joint, caused by impairment of ATFL or both ligaments, cannot be fully restored by any of the reconstructions. However, reconstruction of only ATFL appears to result in better outcomes than combined reconstruction: in the sagittal plane, there is only a small difference between both reconstructions, where reconstruction of only ATFL results in better outcomes (closer to intact condition) than the combined ATFL and CFL reconstruction with augmentation. It can be noticed that both reconstructions result in even larger deviations than the ruptured conditions, which could suggest overtightening of the internalBrace.

These outcomes must help determine whether an isolated ATFL augmentation with the InternalBrace or a combined ATFL and CFL augmentation is more recommended, considering the consequential risks the combined reconstruction takes along. Regarding the location of the CFL, the adjacent structures such as the peroneal tendons and sural nerve, potentially could be damaged by surgical intervention in this area. It is questionable if the potential benefits of an additional CFL augmentation outweighs these risks. Altogether, the combined reconstruction with augmentation of InternalBrace is indeed recommended.

Besides the evaluation of the different conditions during the stance phase of gait, a trapdoor was used to impose the specimens to a more challenging condition by simulating a lateral ankle sprain. Only for the talocrural, tibiocalcaneal and talonavicular joint, slight changes were found in the sagittal plane for ROM. For average angle, a shift towards external rotation was found for the talocrural and tibiocalcaneal joint and a shift in average angle towards dorsiflexion was found for the calcaneocuboid joint. Contrary to what could be expected, no difference was found in the frontal plane, while the simulated inversion motion predominantly takes place in this plane. A possible explanation for this unexpected result could be found in the set-up, since the trapdoor tilted only 15˚ downwards when the heelstrike occured. In the study of Nieuwenhuijzen et al, a mechanism was used where the trapdoor tilted 25˚ downwards when the subjects landed on the plate. [19,] In the latter work, pilot studies showed reproducible and clearly detectable responses in the subjects using 25˚ or more. To minimize the risk of injury for their subjects, the maximum tilting was restricted at 25˚. [19] This might indicate that the 15˚ decline used in the present study was not enough to challenge the cadavers and evoke real inversion movements. However, the integrity of the cadavers was of prior concern. In the in vivo study of Nieuwenhuijzen, subjects could react on the trapdoor inversion event by adapting their muscle activation patterns (the investigated parameters in their study), a natural protection mechanism that our cadavers lack. Therefore, trapdoor tilting was restricted to 15° in our study, which may have restricted the biofidelity of the set-up for creating an inversion trauma in vitro.

In contrast to other cadaveric quasi-static in vitro studies, this work involves a dynamic set-up to investigate the effect of ligament rupture on the individual foot bone kinematics. A cadaveric set-up is necessary since the talus bone is not accessible for measurement with an in vivo set-up in a movement analysis laboratory. Stormont et al. [24] described the superior inversion and eversion stability when the ankle is fully loaded, where the articular surfaces are the most important contributors to this improved stability. Since most lateral ankle sprains occur during a dynamic event (for example walking, running or jumping), an ankle sprain occurs during loading of the joint. In other words, when the specimens experience the dynamic stance phase of gait, the setting will better represent the situations where ankle sprains occur then when a quasi-static set-up is used, where the specimens are positioned in a particular (unloaded) way and an a torsion force is used to simulate the ankle sprain. [4, 22, 28, 29] In the set-up used in this study, the ankle starts to be loaded by the apparatus during the stance phase of gait (from heel strike) similar to the normal loading during walking. This highlights the importance of the dynamic aspect of this study, as the interarticular movements are evaluated during the dynamic stance phase of gait and not in static, loaded or unloaded, position.

In addition the effect of an inversion trauma on the kinematics can be evaluated during this loading phase of gait, where the trapdoor tilts when the ankle starts to be loaded. This might better resemble an inversion trauma than the static set-ups previously described in literature, applying inversion loads on static cadaveric set-ups. [4, 22, 28, 29,]

There are several limitations associated with this study and its cadaveric nature. Firstly, in in vitro studies, there is a lack of neuromuscular control, the role of the intrinsic foot musculature is disregarded and proprioceptive responses cannot be simulated. Literature reported altered muscle activation patterns during walking for patients with CAI. Various muscle activation patterns are described in different studies, generally with involvement of the m. peroneus longus, m. tibialis anterior, m. rectus femoris and m. gluteus medius. Other studies reported reactive muscle activation patterns for healthy test subjects when a sudden inversion occurs. [12, 18] Last-named topics indicate the role of muscle activation patterns in stabilizing the ankle, what cannot be separately investigated in our cadaveric set-up.

Secondly, the process of natural healing cannot be taken into account with the use of cadavers, disregarding the influence of physiologic recovery after the intervention. However, all those factors are present in all existing cadaveric in vitro studies. Furthermore, it must be noted that for reconstructions with augmentation of InternalBrace in patients, the ruptured ligament itself is repaired along the Brostrøm-Gould procedure prior to the augmentation, while in this study, the Brostrøm-Gould repair is omitted. In patients, the InternalBrace will act as a protection of the repaired ligament to avoid too much elongation in the ligaments.

Thirdly, the forces applied to the tendons of the specimens were below physiological magnitudes observed for normal adult population.[1] However, this scaling of the loading conditions is common in all studies where dynamic in vitro experiments were performed, given the concern of maintaining cadaveric integrity following multiple loading, especially when many experimental conditions are being tested as in the current protocol. [19] Despite these lower muscle forces, the motion patterns remain unaffected and the ROM measured during intact condition is similar to the ROM reported in literature, making this set-up is still suitable to explore the kinematics.

Fourthly, the average age of the specimens was relatively high (77,8 years, with ages ranging between 53 and 82 years) and might not be a good representation of the population in which Brostrøm repairs are typically attempted. [6, 21,28,] The quality of the soft tissue of our cadavers might be affected due to aging of the donors. Additionally, with five cadaveric specimens, the sample size of study is to some extent small, although 427 trials were implemented in total since every foot performed multiple steps. Future studies should include subjects that fit the characteristics of the typical patient group eligible for surgical intervention. Furthermore, the additional Brostrøm ligament repair performed in patients, should be included in the protocol; making the set-up more suitable to extrapolate the in vitro findings to real patients.

In conclusion, this work showed that the effect of an ATFL rupture was not restricted to the talocrural joint and the effect of the CFL was not restricted to the subtalar joint, but ligament ruptures affected the entire foot and ankle complex. The combined ligament reconstruction of ATFL and CFL with augmentation of the InternalBrace, was capable of correcting the increased talocrural instability for inversion-eversion movements caused by ATFL and CFL rupture. The potential risks of the additional augmentation of the CFL must be closely evaluated, and further optimization of surgical techniques might be indicated to minimize the risks. The InternalBrace was nevertheless not adequate to correct the subtalar instability for internal-external rotation movements, offering challenges for future investigation to overcome instability in this plane. The effect of a lateral ankle sprain on the foot and ankle kinematics resulted in minimal differences in kinematics, presumably because of the prudent trapdoor set-up used in this work, involving a smaller inversion tilt.

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Appendix

Populaire samenvatting

Enkelverstuikingen zijn een van de vaakst voorkomende letsels, zeker tijdens sportactiviteiten. Bij het grootste deel van de verstuikingen klapt de voet naar binnen, wat resulteert in pijn aan de buitenkant van de enkel. De enkel wordt verstevigd door spieren en pezen, het gewrichtskapsel en ligamenten. Door een enkelverstuiking kunnen deze structuren beschadigd raken, waarbij de ligamenten, meestal een van de buitenste, kunnen uitrekken of zelfs scheuren. De behandeling na een enkelverstuiking is initieel conservatief, idealiter onder begeleiding van een kinesitherapeut. Voor 20-25% van de gevallen blijkt de conservatieve aanpak onvoldoende, waardoor verzwikte enkels blijven optreden en deze patiënten klagen over aanhoudende pijn en een instabiel gevoel. Onderzoek heeft aangetoond dat chronische instabiliteit vaak gepaard gaat met aantastingen in de enkel en voet. Voor deze patiënten kan een operatieve ingreep aangewezen zijn. De meest gebruikte procedure, de Brostøm-Gould procedure, geeft goede resultaten en weinig complicaties, maar studies hebben aangetoond dat het herstelde ligament toch zwakker blijkt te zijn dan een gezond ligament. Hierdoor zijn ze in sommige gevallen alsnog niet sterk genoeg om enkelverzwikkingen te voorkomen; daarbovenop is na de operatie een lange periode van bewegingsbeperking aangewezen om het herstelde ligament te beschermen. Nieuwe technieken werden ontwikkeld om aan deze beperkingen tegemoet te komen, waaronder de InternalBrace (Arthrex) die het herstelde ligament gaat overbruggen voor extra stevigheid en bescherming. Verschillende studies hebben al bewezen dat de InternalBrace-reconstructie veel sterker was.

Deze studie ging het effect van gescheurde ligamenten na op de bewegingen in de enkel en verschillende voetgewrichten, evenals het effect van de InternalBrace om de gescheurde ligamenten te overbruggen. Op die manier werden vijf verschillende condities gecreëerd: de voet met intacte ligamenten, met één doorgesneden ligament, met twee doorgesneden ligamenten, met overbrugging van de InternalBrace voor één ligament en overbrugging voor twee ligamenten. Daarbovenop werd het effect nagegaan van een nagebootste enkelverstuiking (waarbij de voet naar binnen klapt) op deze bewegingen in de enkel- en voetgewrichtjes. Om deze elementen te kunnen onderzoeken, werden vijf kadavervoeten gebruikt. De voeten werden gemonteerd op een gangsimulator die er de steunfase van de gangcyclus mee kan nabootsen, waarbij ondertussen de bewegingen in de enkel- en voetgewrichten werden geregistreerd aan de hand van een 3D-camera. Op basis hiervan kon de invloed van een bepaalde conditie (vb 1 gescheurd ligament) op de bewegingen in de enkel- en voetgewrichten tijdens de steunfase van de gangcyclus, worden geëvalueerd.

De resultaten van deze studie toonden aan dat een scheur van de ligamenten niet alleen invloed had op de bewegingen in het gewricht waar ze primair voor instaan, maar dat ook beweging in andere gewrichten werd beïnvloed.
Toepassing van de gecombineerde overbrugging met de InternalBrace kon voornamelijk voor de enkel de verstoorde beweging herstellen. De InternalBrace was echter niet in staat alle bewegingsverstoringen in andere gewrichten op te heffen.
De resultaten van de nagebootste enkelverstuiking bleken niet sterk verschillend van de gewone stapcyclus, tegen de verwachtingen in. Mogelijks was de gehanteerde kanteling te klein om een reële enkelverstuiking na te bootsen.

Appendix

Master in de revalidatiewetenschappen en de kinesitherapie (Leuven e.a.)

CAT 5: Het onderzoek maakt gebruik van bestaand lichaamsmateriaal (bloed, urine, weefsel...).

Openstaande aanvragen 0

	Reg. nr.	Titel van de studie	Status	Beheer

Aanvragen voor advies bij CTC/EC 0

Gunstig advies van OBC 1

	Reg. nr.	Titel van de studie	Status	Beheer
	mp16948	Het effect van ligament ruptuur en ligament herstel op de kinematica tijdens het gaan - in vitro studie **Student(en):** Nette D'Haene **Promotor:** Ilse Jonkers	Gunstig advies van OBC	

Geweigerde aanvragen 0

Appendix

Richtlijnen voor auteurs voor publicaties van de GUIDELINES FOR AUTHORS in Clinical Biomechanics:

http://courses.washington.edu/bioen520/notes/AJSM_Submission_Guidelines.pdf