<u>Title:</u> Augmented ligament reconstruction partially restores hind and midfoot kinematics following lateral ligament ruptures

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Augmented ligament reconstruction partially restores hind and midfoot kinematics following lateral ligament ruptures

Abstract

Background: Ligament augmentation with suture tape (InternalBrace, Arthrex Inc, United States) resulted in improved AOFAS scores compared to pre-surgery and compared to the classical Broström-Gould procedure, but the ability to restore foot-ankle gait kinematics has not been investigated. This is important since altered kinematics and persisting ankle instability have been associated with degenerative changes and osteochondral lesions.

Purpose: Study the effect of ligament reconstruction surgery with suture tape augmentation (isolated ATFL vs. combined ATFL and CFL) after lateral ligament ruptures (combined ATFL and CFL) on foot-ankle kinematics during simulated gait.

Study Design: Descriptive Laboratory Study

Methods: Five fresh-frozen cadaver specimens were tested in a custom-built gait simulator in five different conditions: intact, ATFL rupture, ATFL-CFL rupture, ATFL-CFL reconstruction and ATFL reconstruction. For each condition, the range of motion and average angle in the hind- and midfoot joints were calculated during the stance phase of normal and inverted gait.

Results: Ligament rupture mainly changed the range of motion in the hindfoot and the average angle in hindfoot and midfoot and influenced the kinematics in all three movement directions. A combined ligament reconstruction was able to restore the range of motion in inversion-eversion in four of the five joints and the range of motion in internal-external rotation and dorsi-plantarflexion in three of the five joints. It was also able to restore the average angle in inversion-eversion in two of the five joints, in internal-external rotation in all joints and in dorsi-plantarflexion in one of the joints. An isolated ATFL reconstruction was able to restore the range of motion in inversion-eversion and internal-external rotation in three of the five joints and the range of motion in dorsi-plantarflexion in two of the five joints. The isolated reconstruction was also able to restore the average angle in inversion-eversion and dorsi-plantarflexion in two of the joints and in internal-external rotation in three of the joints. Both reconstructions were most successful in restoring the motion in the tibiocalcaneal and talonavicular joint and least successful in restoring the motion in the talocalcaneal joint. However, the combined reconstruction was still better in restoring the motion in the talocalcaneal joint than the isolated reconstruction (1/3 for the range of motion and 0/3 for the average angle with the isolated reconstruction compared to 1/3 for the range of motion and 2/3 for the average angle with the combined reconstruction).

Conclusion: A combined ATFL-CFL reconstruction shows better restored motion immediately after surgery than an isolated ATFL reconstruction after a combined ATFL and CFL rupture.

Clinical Relevance: This study shows that a ligament reconstruction with suture tape augmentation is able to partially restore the kinematics in the hind- and midfoot at the time of the surgery. In clinical applications, where the classical Broström-Gould procedure is followed by augmentation with the suture tape, this procedure may protect the repaired ligament during healing by limiting the excessive range of motion following ligament rupture.

Key Terms: lateral ligament reconstruction, foot-ankle kinematics, ligament rupture, gait simulation

What is known about the subject: Previous studies showed improved AOFAS scores after suture tape augmentation compared to pre-surgery and compared to the classical Broström-Gould procedure (at the same time post-surgery). Additionally, they showed a faster return to sports (based on questionnaires). Furthermore, previous studies showed that ligament surgery with suture tape augmentation results in a stronger ligament compared to the intact ligament and to other repairs. However, to our knowledge, no previous studies investigated if the ligament reconstruction with suture tape augmentation is able to restore the altered hind- and midfoot kinematics caused by a combined ATFL & CFL rupture.

What this study adds to existing knowledge: With the set-up of this study, we were able to evaluate and quantify the effect of ligament rupture and ligament reconstruction on gait kinematics of the individual hind and midfoot foot bones. This allowed us to evaluate if the ligament reconstruction using suture tape was able to restore the kinematics during normal and inverted gait. This is important since persistence of altered foot-ankle kinematics have been associated with osteochondral lesions and consequent degenerative changes. In addition, this study evaluates the ability of the suture tape to protect the Broström-Gould repair and thereby to allow a faster rehabilitation.

Introduction

Ankle sprains are one of the most frequently treated musculoskeletal injuries with a high incidence in the general population and during sports activities[22,36]. Although ankle sprains can occur during inversion, eversion or hyperdorsiflexion of the foot, 85% of the sprains result from an inversion trauma of the foot rupturing the anterior talofibular ligament (ATFL) in 85 % of the cases[11]. An additional rupture of the calcaneofibular ligament (CFL) is less frequent (20% of the patients)[4]. After an ankle sprain, a short time of immobilisation may be helpful in relieving pain and swelling[3,36]. However, patients benefit most from using bracing and taping in combination with an exercise program to improve the ankle stability[2,36]. Although ankle sprains are frequently considered minor injuries, they are painful and limit weight bearing activities. In addition, 30-50% of the patients[10,23,30] will have persistent symptoms (e.g. ankle instability, swelling or recurrent ankle sprains) after the first weeks of conservative treatment. Those persistent symptoms can lead to secondary problems such as, chronic ankle instability, altered ankle kinematics[7], chondral injuries[33] and ankle osteoarthritis[34]. In those patients and high demanding athletes, a surgical intervention is therefore considered[1,2].

Of these, anatomical procedures are typically 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[5,20,29]. The Broström technique is considered a 'golden standard'[5]. Although good post-operative subjective ankle stability is achieved[32], this ligament restoration may not be strong enough to avoid sprain recurrence during physical activity[14]. Additionally, post-operative immobilisation is required which delays the rehabilitation and can cause tissue degeneration[27]. Consequently, alternative or adapted surgery techniques based on the original Broström technique have been developed. One recent technique augments the Broström repair with extra structural support, such as a suture tape[26]. As a result, the repaired ligament has higher loads-to-failure[35] and results in good subjective ankle stability[8].

The suture tape augmentation also improved the mean post-operative AOFAS score and resulted in a faster improvement in the AOFAS score compared to the Broström-Gould repair without suture tape augmentation[38]. However, to our knowledge, the ability of the surgery with suture tape augmentation to restore foot-ankle kinematics during gait has not been studied previously. This is important since previous studies showed that altered kinematics and sustained ankle instability can lead to degenerative changes and osteochondral lesions[25,34].

Therefore, in this in vitro study, 3D motion capture was used to measure foot bone kinematics after ligament rupture and ligament reconstruction (for a combined rupture) using a suture tape augmentation during the stance phase of gait simulated with an in-house developed gait simulator. We hypothesized that an ATFL rupture would mainly influence the tibiotalar kinematics and the combined ATFL-CFL rupture the subtalar kinematics. Additionally, we hypothesized that an isolated reconstruction would only be able to restore the tibiotalar kinematics but not the subtalar kinematics induced by a combined ligament injury.

Methods

Cadaver specimens

Five freshly frozen lower leg cadaveric specimens without a medical history of major foot and ankle pathologies were obtained via Science Care (Science Care, United States) and amputated mid-tibially. These specimens were tested in five different conditions: the intact foot, the foot with ATFL resection, the foot with ATFL and CFL resection, the foot with combined ATFL and CFL reconstruction and the foot with an isolated reconstruction of ATFL but resected CFL.

Ligament resection and surgical reconstruction

All procedures were performed by an experienced orthopaedic surgeon (SV) while the specimen was attached to the gait simulator[18]. Standard instrumentation and techniques representative of the clinical setting were used. First, an anterolateral incision of 4cm was made at the anterior border of the lateral malleolus and sinus tarsi where a lateral arthrotomy was performed to visualise and resect the ATFL and CFL. The ATFL was cut at the insertion on the talus, whereas the CFL was cut at the origin on the tip of the fibula.

For the ATFL reconstruction, a 3.5mm drill hole (angled proximally) was made over the anatomic ATFL origin into the anterior border of the lateral malleolus. The hole was tapped with a 3.5mm tap and a loaded suture anchor (3.5mm Swivelock biocomposite anchor, Arthrex, United States) was inserted with 2 bundles of suture tape (InternalBrace, Arthrex, United States). At the talar neck, around 1 cm anterior and superior to the sinus tarsi, a 4.75mm drill hole (45 degrees posteromedially) was made at the anatomical insertion of the ATFL. The talar tunnel was taped with the 4.75mm tap and one of the suture tape bundles was inserted into the talar tunnel and fixed with another suture anchor (4.5mm). The second bundle of suture tape was positioned underneath the peroneal tendons. Finally, a 3.5mm drill hole (inferiorly and posteriorly) was made in the lateral wall of the calcaneus over the CFL anatomic insertion and was taped with a 3.5mm tap. Afterwards, the second bundle was fixed with a third knotless suture anchor (3.5mm).

Both suture tapes were put under maximal tension, but taking care not to overtighten the construction. To finish the reconstruction, the remainders of the suture tape were cut out. After testing the combined ATFL and CFL reconstruction, the CFL suture tape was cut to test the isolated ATFL reconstruction.

Figure 1: Schematic representation of the ligament reconstructions. The grey zones are the drill direction of the holes. The blue lines indicate the positioning of the suture tape.

Gait simulator and in vitro foot bone kinematics calculation

For the in vitro tests, the specimens were attached to a custom-built cadaveric gait simulator (Supplementary Material - Figure A). Within this simulator, cadavers are tested dynamically by applying muscles forces representative for the stance phase of gait using pneumatic actuators attached to the tendons of six muscle-groups (m. tibialis anterior + m. extensor hallucis longus + m. extensor digitorum longus, m. peroneus longus + m. peroneus brevis, m. gastrocnemius + m. soleus, m. tibialis posterior, m. flexor hallucis longus, m. flexor digitorum longus). The anterior displacement and flexion-extension around the knee axis are induced by electro-server motors and the ground reaction forces are simulated by the upwards movement of the force plate controlled by the induced movement of the foot and ankle. This set-up has been previously validated and described in literature[6,18,19,24].

Each foot was tested in two modalities, for which a set of ten measurements was performed: First, normal overground gait was simulated similar to the published work[6,18,19,24]. Second, inversion was enforced during gait using a trapdoor that induced an inclination of 15° of the floor surface (Supplementary Material – Figure B). The trapdoor is used to create a more challenging condition and is described in a study by Nieuwenhuijzen et al.[21].

Hindfoot kinematics were measured using 3D motion capture (Krypton, Metrix, Belgium, accuracy 90 micron, sampling frequency 100Hz). A bone pin was inserted in tibia, talus, calcaneus, cuboid and navicular. On these pins, a cluster of four leds was placed. The 3D position of the leds (measured by the 3D motion capture) was combined with CT-based information, to calculate the 3D bone relative angles. Inversion-eversion was defined as the movement around the anterior-posterior axis, internal-external rotation as the movement around the proximal-distal axis and dorsiflexion-plantar flexion as the movement around the medial-lateral axis. The calculated angles were filtered with a 6 HZ low-pass filter (Matlab , The Matworks Inc, United States).

From the kinematics, two parameters were calculated: the range of motion (ROM) i.e. difference between the extreme joint positions, and the average angle (AA) during the stance phase of normal and trap door walking (Figure 2). The ROM reflects the effect of ligament rupture and ligament reconstruction on the movement excursion, whereas the AA reflects their effect on the dynamic foot alignment. Both parameters were calculated for the tibiotalar, talocalcaneal, tibiocalcaneal, talonavicular and calcaneocuboid joint.

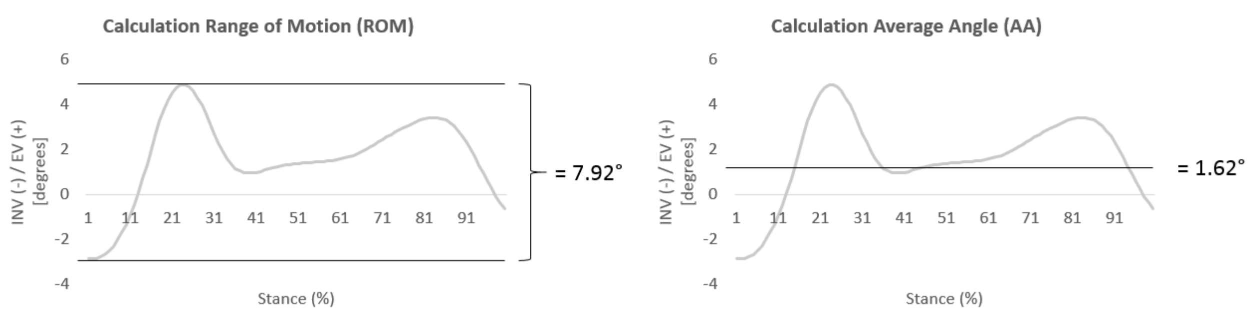


Figure 2: Calculation of the range of motion (ROM) defined as the difference (in degrees) between the two extreme joint positions and the calculation of the average angle (AA) as the mean value over the stance phase of gait.

Statistics

Statistical analysis was performed using Matlab (The MathWorks Inc, United States). A general linear mixed model for repeated measures was fitted to evaluate the effect of ligament rupture (ATFL and ATFL + CFL), type of reconstruction (ATFL and ATFL + CFL) and walking condition (normal vs trapdoor) on the ROM and the AA in the five different joints. A variable intercept was used to correct for differences in intact walking between subjects (random effect). A fixed-effect was included for the conditions and the measurement types (normal walking and trapdoor walking) and a random effect for the different subjects was included. For all tests, the significance level was set at $\alpha=0.05$.

The difference between the ROM and AA during intact walking, and the ROM and AA during gait with an isolated or combined ligament rupture, and the ROM and AA during an isolated or combined ligament reconstruction were calculated and plotted. Changes in ROM or AA that were within the standard deviations observed during normal walking were considered as not clinically relevant and are not reported.

Results

Influence of ligament rupture and ligament reconstruction

Isolated ATFL rupture

An isolated ATFL rupture increased ROM in inversion-eversion in the tibiotalar ($p=0.003$, +21.52%) and talonavicular joint ($p<0.001$, +32.55%) (Figure 3A), increased ROM in internal-external rotation in the talocalcaneal joint ($p=0.017$, +67.14%) (Figure 4A), but decreased ROM in dorsi-plantar flexion in the tibiotalar ($p<0.001$, -10.60%) and tibiocalcaneal joint ($p<0.001$, -15.54%) (Figure 5A). Additionally, the isolated ATFL rupture increased the AA of external rotation (Figure 4B) and dorsiflexion (Figure 5B) in the tibiotalar ($p<0.001$, +15.93% external rotation and +40.03% dorsiflexion) and talonavicular joint ($p<0.001$, +138.37% external rotation and +40.80% dorsiflexion), of the external rotation in the talocalcaneal joint (p=0.043, +74.51%) (Figure 4B), of the dorsiflexion in the tibiocalcaneal joint (p<0.001, +109.70%) (Figure 5B) and of the plantar flexion in the calcaneocuboid joint (p=0.039, +36.41%) (Figure 5B).

Combined ATFL-CFL rupture

A combined ATFL-CFL rupture increased even more the ROM in inversion-eversion in the tibiotalar (p<0.001, +49.96%) (Figure 3A) and talocalcaneal joint (p<0.001, +73.35%) (Figure 3A) and the ROM in internal-external rotation in the talocalcaneal joint (p=0.017, +86.56%) (Figure 4A). Additionally, the combined rupture decreased the dorsi-plantar flexion ROM in the tibiotalar joint (p=0.002, -33.03%) but increased it in the calcaneocuboid joint (p<0.001, +14.21%) (Figure 5A). The combined rupture also increased the AA of the eversion in the tibiotalar (p<0.001, +354.74%) and talonavicular joint (p=0.007, +9.54%) (Figure 3B), of the inversion in the talocalcaneal joint (p<0.001, +101.31%) (Figure 3B) and of the dorsiflexion in the tibiotalar joint (p<0.001, +56.12%) (Figure 5B).

Isolated ATFL reconstruction

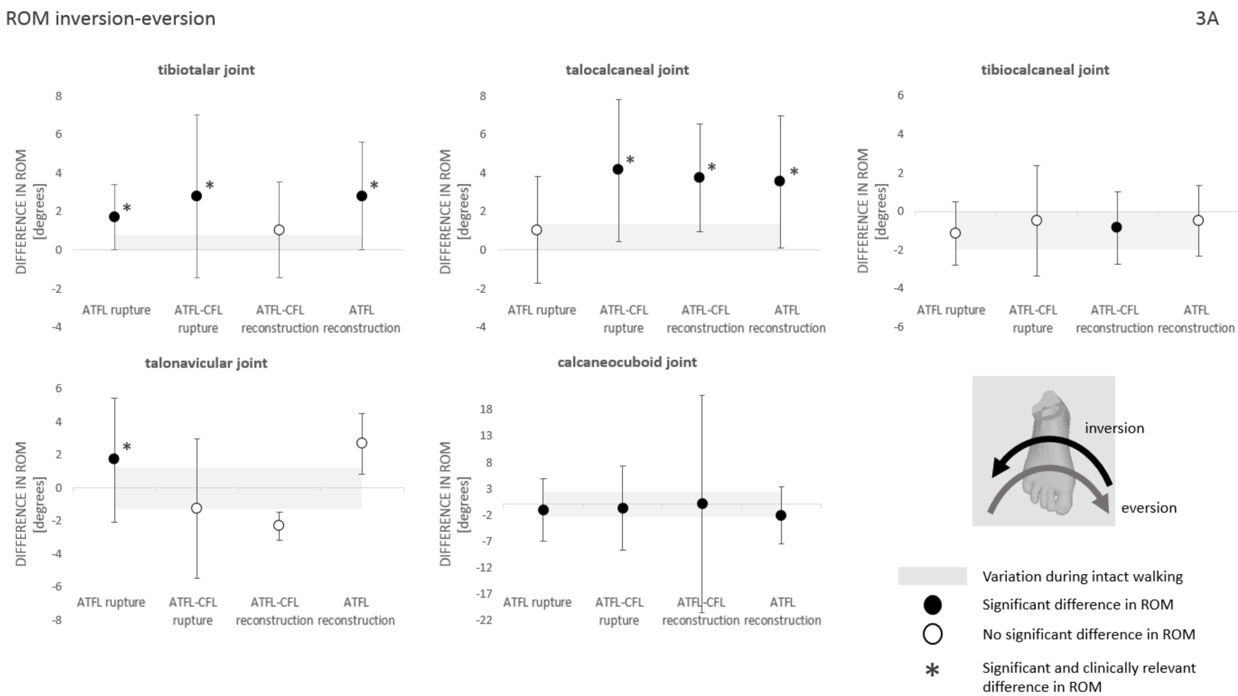
There was no significant difference between an isolated ATFL reconstruction and the intact condition for inversion-eversion ROM in the talonavicular joint (p=0.193) (Figure 3A), the internal-external rotation AA in the tibiotalar (p=0.07) and the talonavicular joint (p=0.36) (Figure 4B) and the dorsi-plantar flexion AA in the tibiocalcaneal (p=0.095) and calcaneocuboid joint (p=0.517) (Figure 5B). There was a significant difference between the isolated ATFL reconstruction and the intact condition for the inversion-eversion ROM in the tibiotalar joint (p<0.001, +30.36%) (Figure 3A) and the dorsi-plantar flexion ROM in the tibiotalar (p<0.001, -40.71%), tibiocalcaneal (p<0.001, -32.89%) and calcaneocuboid joint (p<0.001, +105.31%) (Figure 5A). There was also a significant difference between the isolated ATFL reconstruction and the intact condition for the inversion-eversion AA in the tibiotalar (p<0.001, +269.24% to eversion), talocalcaneal (p<0.001, +84.15% to inversion) and talonavicular joint (p<0.001, +40.88% to eversion) (Figure 3B) and the dorsi-plantar flexion AA in the talocalcaneal (p<0.001, +62.23% to dorsiflexion) and talonavicular joint (p<0.001, +4.72% to dorsiflexion) (Figure 5B). The isolated reconstruction even resulted in an additional increased ROM in internal-external rotation in the calcaneocuboid joint (p<0.001, +3.47%) (Figure 4A), in an increased external rotation AA in the tibiocalcaneal joint (p=0.002, +894.25%) (Figure 4B) and an increased dorsiflexion AA in the talocalcaneal joint (p<0.001, +62.23%) (Figure 5B).

Combined ATFL-CFL reconstruction

There was no significant difference compared to intact inversion-eversion ROM in the tibiotalar (p=0.333) and talonavicular joint (p=0.07) (Figure 3A) and the dorsi-plantar flexion ROM in the tibiocalcaneal joint (p=0.49) (Figure 5A). There was also no significant difference in the inversion-eversion AA in the tibiocalcaneal joint (p=0.942) (Figure 3B), the internal-external rotation AA in the tibiotalar (p=0.28) and talocalcaneal joint (p=0.11) (Figure 4B) and the dorsi-plantar flexion AA in the tibiocalcaneal joint (p=0.11) (Figure 5B) compared to intact walking. There was a significant difference between the combined reconstruction and the intact condition for the inversion-eversion (p=0.023) (Figure 3A) and internal-external rotation (p=0.002) ROM (Figure 4A) in the talocalcaneal joint (+59.16% in inversion-eversion and +62.53% in internal-external rotation) and the dorsi-plantar flexion ROM in the tibiotalar (p<0.001, -50.91%) and calcaneocuboid joint (p=0.039, +60.96%) (Figure 5A). There was also a significant difference between the combined reconstruction and the intact condition for the inversion-eversion (p=0.021, +168.5% to eversion) (Figure 3B) and internal-external rotation (p=0.04, +126.65% to external rotation) AA (Figure 4B) in the talonavicular joint and the dorsi-plantar flexion AA in the tibiotalar (p<0.001, +47.54% to dorsiflexion), talocalcaneal (p=0.02, +1.92% to dorsiflexion), talonavicular (p<0.001, +20.74% to dorsiflexion) and calcaneocuboid joint (p=0.039, +280.23% to dorsiflexion) (Figure 5B). The combined reconstruction additionally increased inversion AA in the calcaneocuboid joint (p<0.001, +238.83%) (Figure 3B).

Influence of trapdoor walking

Walking on the trapdoor decreased plantar-dorsiflexion ROM in the tibiotalar ($p<0.001$, -16.02%) joint and an increased plantar-dorsiflexion ROM in the talonavicular ($p<0.001$, +17.21%) joint compared to normal walking (Figure 6 – left). The trapdoor increased external rotation AA in the tibiotalar ($p<0.001$, +17.67%) and tibiocalcaneal ($p=0.03$, +43.88%) joint and dorsiflexion AA in the calcaneocuboid joint ($p=0.011$, +3.54%) (Figure 6 – right). The trapdoor did not change the ROM or dynamic alignment in the other movement directions or joints (Figure 6).



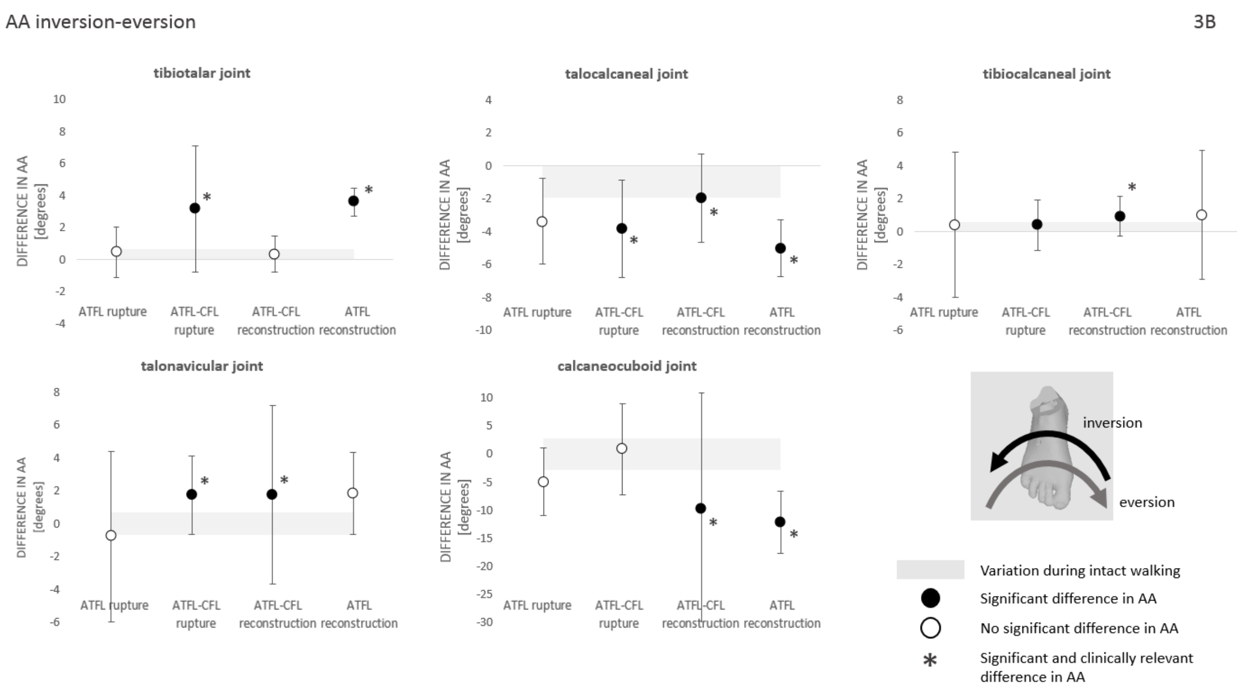
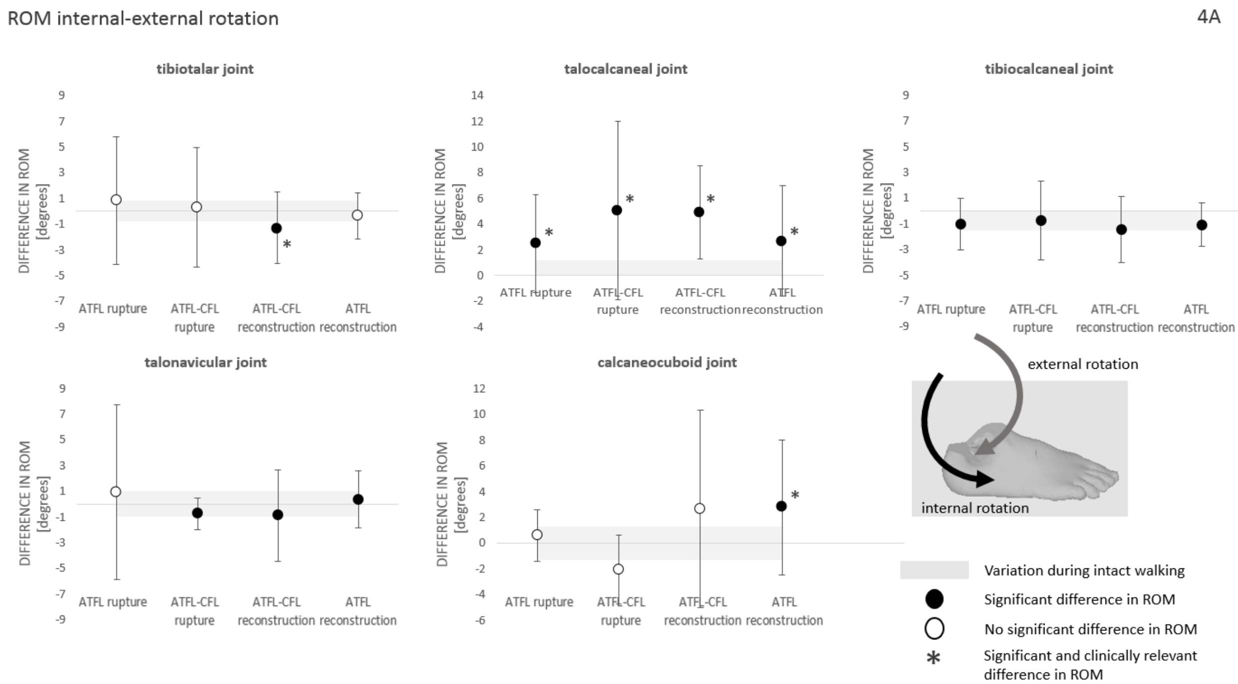


Figure 3: Average difference and 95% confidence intervals for the ROM (3A) and AA (3B) compared to the intact condition in inversion-eversion. A positive value indicates increased ROM (3A) or increased eversion (3B) compared to the intact condition. Y-axis range is set at 12° degrees for the ROM and 14° for the AA, except for the ROM and AA in the calcaneocuboid joint.



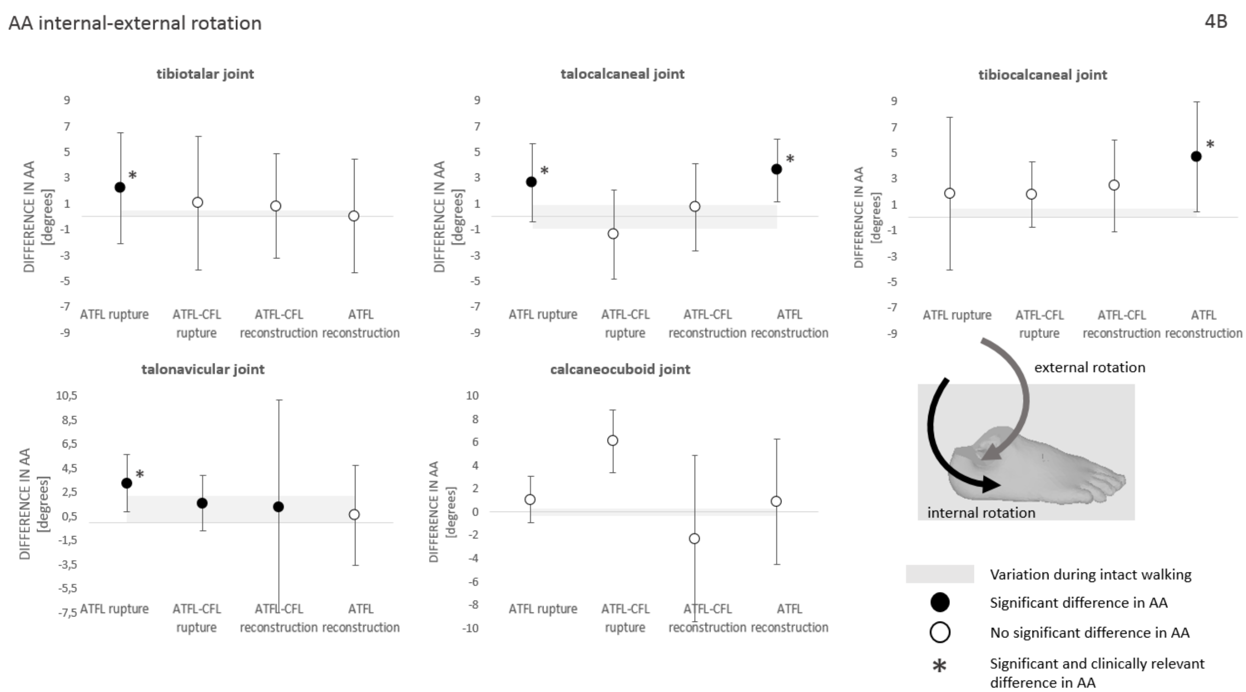
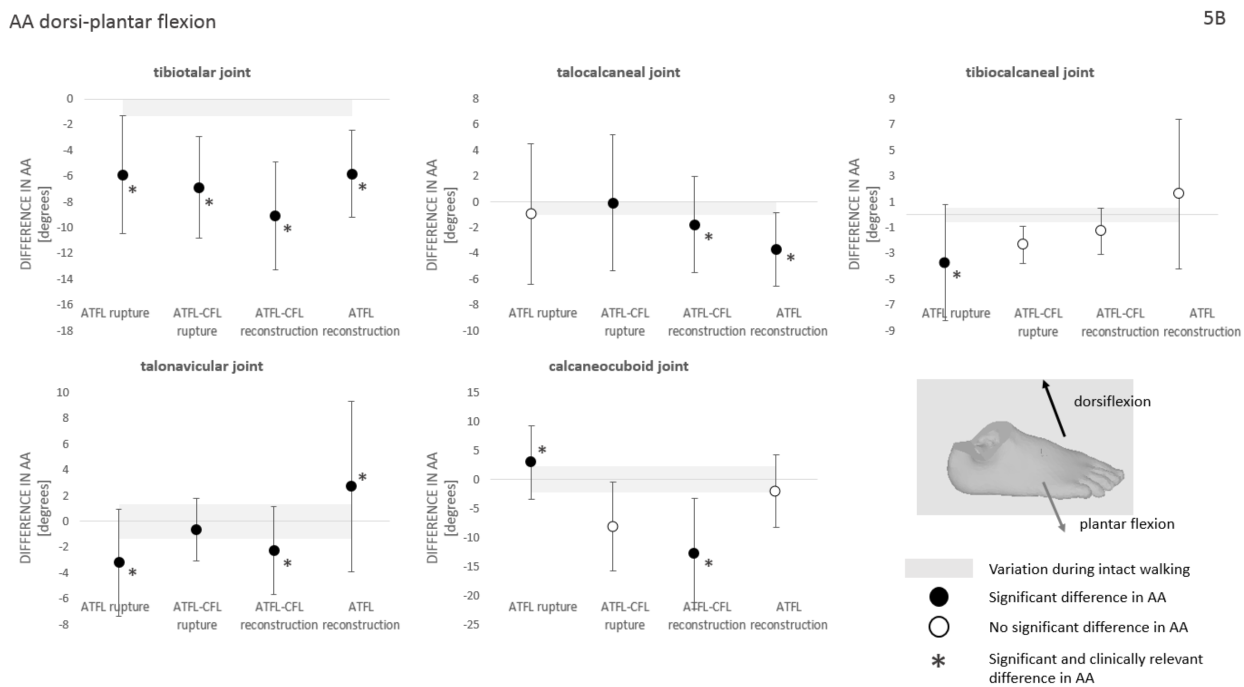


Figure 4: Average difference and 95% confidence intervals for the ROM (4A) and AA (4B) compared to the intact condition in internal-external rotation. A positive value indicates increased ROM (4A) or an increased external rotation (4B) compared to the intact condition. Y-axis range is set at 18° degrees for the ROM and for the AA, except for the AA in the calcaneocuboid joint.



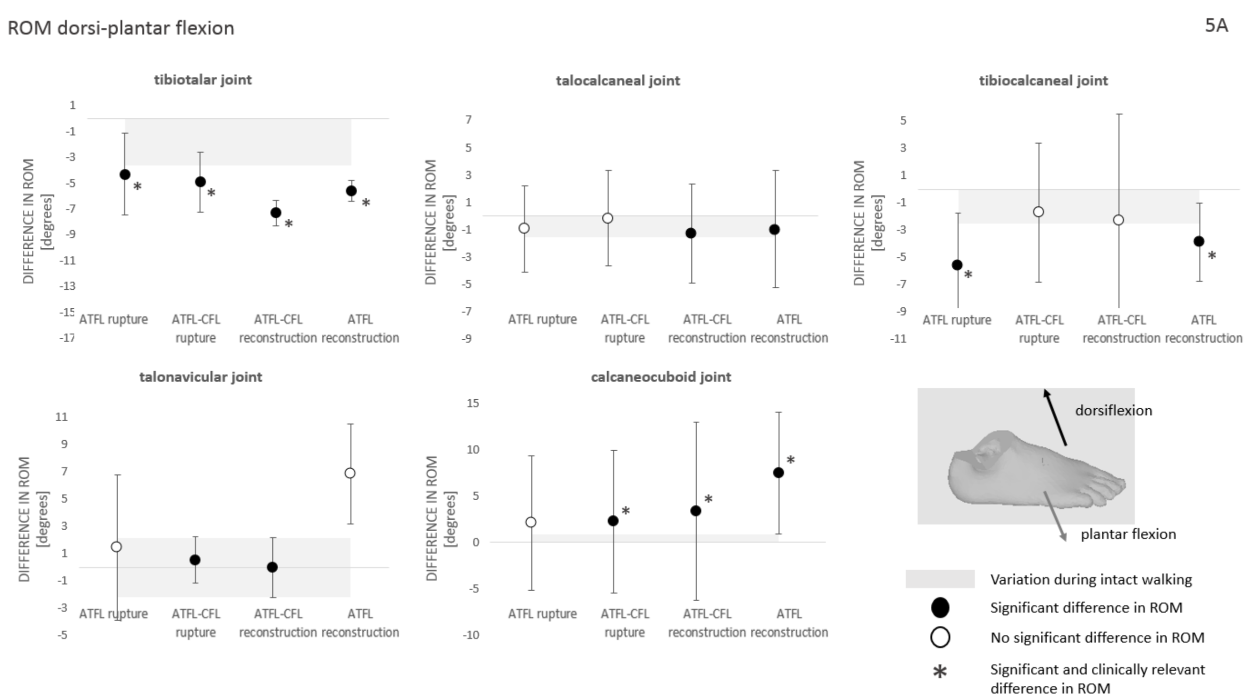


Figure 5: Average difference and 95% confidence intervals for the dorsi-plantar flexion ROM (5A) and AA (5B) compared to the intact condition. A positive value indicates increased ROM (5A) or an increased plantar flexion (5B) compared to the intact condition. Y-axis range is set at 17° degrees for the ROM and 18° for the AA, except for the ROM and AA in the calcaneocuboid joint.

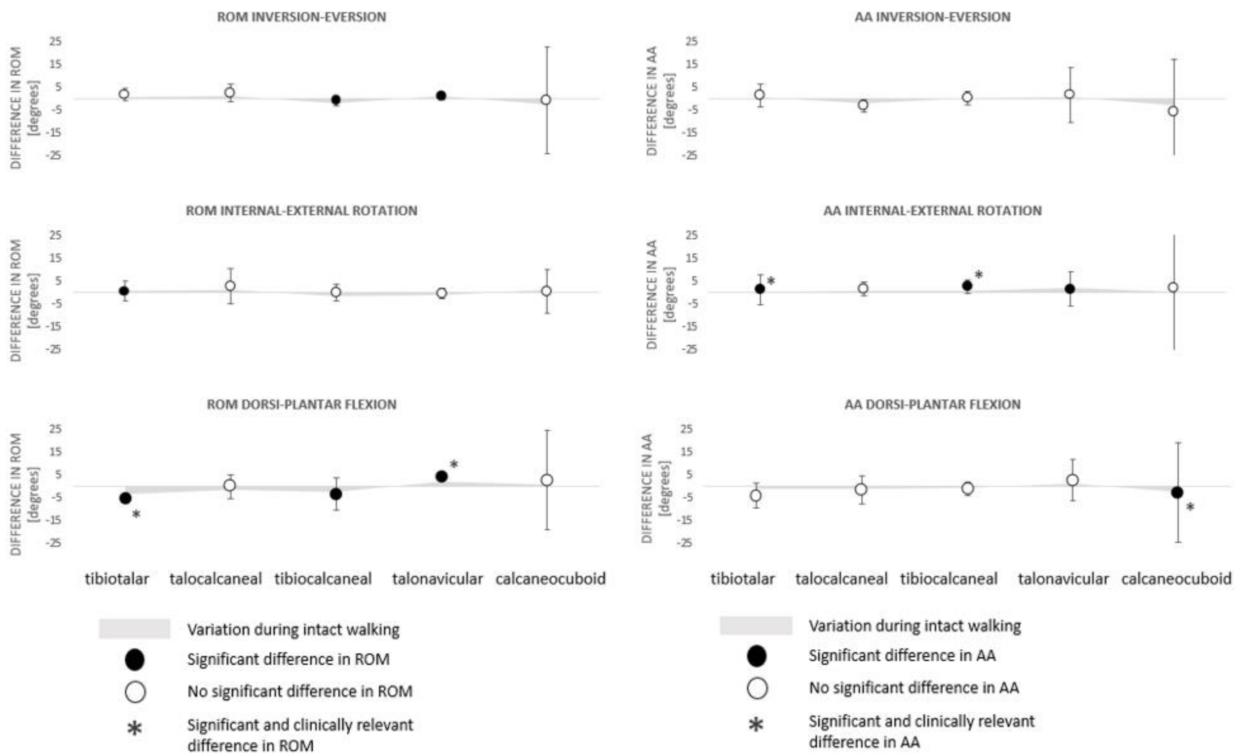


Figure 6: Average difference and 95% confidence intervals for the ROM (left) and AA (right) during inverted walking compared to normal walking in the three movement directions. A positive value indicates increased ROM (left) or increased eversion, external rotation and plantar flexion (right) compared to normal walking. Y-axis range is set at 50° degrees for the ROM and AA.

Discussion

In this study, the effect of individual and combined ligament rupture (ATFL and ATFL + CFL) and reconstruction (ATFL and ATFL + CFL) on the kinematics during normal and inverted walking were evaluated based on the movement excursion (ROM) and the dynamic alignment (AA) in the tibiotalar, talocalcaneal, tibiocalcaneal, talonavicular and calcaneocuboid joints. In general, as the ligament reconstruction procedures were able to at least partially restore the aberrant kinematics caused by the ligament rupture, we conclude that the suture tape augmentation is efficient in restoring hind- and midfoot instability following ligament rupture at the time of the surgery. However, it's effect on ligament healing remains unknown.

As expected based on anatomy, an isolated ATFL rupture increased inversion-eversion ROM in the tibiotalar joint, while an additional CFL rupture increased the in inversion-eversion ROM even more and induced increased inversion-eversion ROM and excessive inversion AA in the talocalcaneal joint. These latter changes are in accordance with the anatomical position of the CFL, being the only ligament covering both the tibiotalar and talocalcaneal joint[16]. Consequently, for a combined ATFL and CFL rupture, only a combined ATFL-CFL reconstruction was able to fully restore the altered kinematics in tibiotalar and partially restore the changes in talocalcaneal joint, whereas an isolated ATFL reconstruction was ineffective in restoring the tibiocalcaneal frontal plane kinematics.

A lateral ligament rupture did not only change the frontal plane, but also the transverse plane kinematics. An isolated ATFL rupture increased the internal-external ROM in the talocalcaneal joint and an additional CFL rupture further increased this ROM. In contrast to the frontal plane, none of the ligament reconstructions were able to completely restore the transverse plane kinematic changes.

Finally, the ligament ruptures also influenced the sagittal plane kinematics. Both the isolated and combined injury decreased plantar-dorsiflexion ROM in the tibiotalar joint but in an increased plantarflexion AA in the tibiotalar joint. Both ligament reconstructions were not able to fully restore these changes.

Overall after a combined ATFL and CFL rupture, a combined ATFL-CFL reconstruction better restored normal motion than an isolated ATFL reconstruction, especially for the frontal plane ROM and AA. This is in contrast with the study of Pereira et al. where no significant differences were found in the kinematics after an isolated and a combined ligament reconstruction. However, in this study, the cadaver specimens were subjected to an inversion of 20°, which is more challenging than the normal and trapdoor gait that was investigated in this study. Although surgeons think a combined reconstruction may benefit the patients, CFL reconstruction surgery is not always considered, given its location underneath the peroneal tendons, close to the sural nerve[28]. It is therefore still questionable if the potential benefits of an additional CFL repair and augmentation outweigh these risks.

It needs to be considered that the ligament reconstruction surgery performed in vitro differs from the ligament surgery performed in vivo. In the clinics, the surgeon first repairs the original ligament with the Broström-Gould procedure and afterwards augments this repair with the suture tape. In this study, only the ligament reconstruction with the suture tape was performed. The findings of this study indicate that the ligament reconstruction with suture tape is able to restore the ROM to physiological values in the hind- and midfoot joints as well as to partially restore the dynamic foot alignment. Consequently, the ligament reconstruction using suture tape could potentially protect the repaired ligament against stretching during the healing process and possibly allow a faster rehabilitation. Additionally, previous studies showed a decreased performance of the Broström repair after several years by stretching the repaired ligament[14]. The suture tape augmentation might be able to prevent this by decreasing the stretch on the repaired ligament from the beginning.

Evaluation of lateral ligament reconstruction procedures cannot be limited to evaluating the hindfoot kinematics in isolation, but should include evaluation of the midfoot kinematics since a lateral ligament rupture changes hind- as well as midfoot kinematics. Previous in vitro and in vivo studies used the anterior drawer and talar tilt test to evaluate the success of the ligament surgery, thereby only evaluating the tibiotalar and talocalcaneal joint in inversion-eversion and dorsi-plantar flexion[9,37]. With the in vitro set-up used in this study, the effect of ATFL and CFL rupture on the midfoot kinematics was confirmed: An ATFL rupture increased inversion-eversion ROM in the talonavicular joint, increased inversion AA and external rotation in the talonavicular joint and increased plantar flexion AA in the calcaneocuboid joint. A combined ATFL-CFL rupture further increased the plantar-dorsiflexion ROM in the calcaneocuboid joint and an increased eversion AA in the talonavicular joint. The inclusion of midfoot evaluation is in particular important to evaluate the risk of ligament overtightening. Indeed, compensatory changes in the midfoot kinematics were found after ligament surgery: A combined reconstruction changed the dynamic inversion-eversion alignment in the calcaneocuboid joint whereas an isolated ATFL reconstruction altered the internal-external rotation ROM and AA in the calcaneocuboid joint.

A trapdoor was used to evaluate the effect of ligament rupture and consequent ligament reconstruction in more challenging conditions. The trapdoor was previously used to simulate a lateral ankle sprain[21]. However, only slight differences in kinematics were observed during trapdoor compared to normal walking. However, to protect the integrity of the cadavers, the trapdoor only tilted 15° at heelstrike, whereas typically a tilt of 25° is used in patients with chronical ankle instability[21] in vivo.

There are several limitations associated with this in vitro study. Firstly, although we did impose muscle forces representative to stance phase of normal gait, the role of the intrinsic foot musculature and proprioceptive responses due to neuromuscular control following inversion were disregarded. Studies showed changes in m. peroneus longus, m. tibialis anterior, m. rectus femoris and m. gluteus medius in patients with chronical ankle instability and in healthy volunteers during increased inversion angles[12,21]. Therefore, the role of muscle activation in ankle stabilization was not investigated in our cadaveric set-up and only the isolated effect of a ligament rupture and consequent reconstruction on the hind- and midfoot kinematics during stance phase of gait can be studied. Secondly, the natural healing process cannot be taken into account. However, this study showed that the ligament reconstruction using suture tape augmentation is able to protect the Broström-Gould repair at the time of surgery. Thirdly, the changes in kinematics after ligament rupture in this study, especially in internal-external rotation, do not fully match with the findings in literature[13,17]. However, these changes in internal-external rotation were mainly captured in the talocalcaneal joint, whereas in vivo studies report changes in the tibiocalcaneal alignment and cannot isolate the movements between tibiotalar and talocalcaneal joints. 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 young population in which Broström repairs are typically performed[15,31,35]. Indeed, the soft tissue quality might be affected due to aging of the donors, but the use of cadaver samples allows to study the influence of the ligament rupture and reconstruction on individual foot bone motion, which cannot be measured in in-vivo studies. Finally, this study was under powered to detect all of the differences since only five cadaveric specimens were measured.

In conclusion, this work showed that the combined ATFL-CFL ligament reconstruction was able to mostly correct the instability in inversion-eversion caused by the combined ligament rupture at time zero. The potential risks of an additional CFL augmentation must be closely evaluated and further optimization of surgical techniques might be indicated to minimise the risks. The suture tape augmentation was not sufficient to correct the talocalcaneal instability in internal-external rotation and could only partially correct the changes in the midfoot, highlighting the need for future investigations on optimized surgical interventions to overcome these persistent instabilities.

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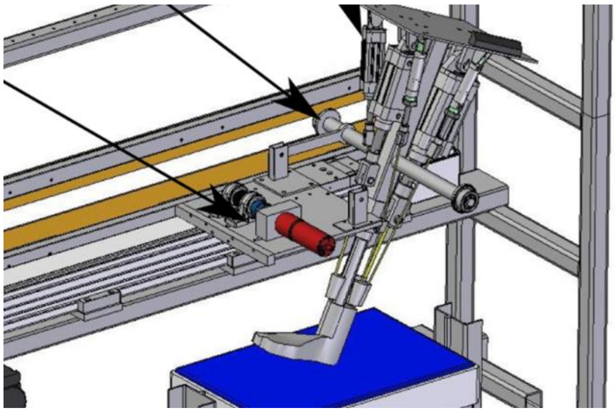
Supplementary Material



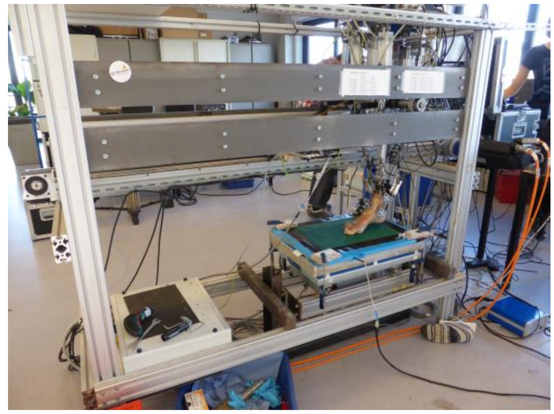


Figure A: Gait simulator set-up. On the left figure, you can see the positioning of the two electro server motors. They are responsible for the horizontal translation and the rotation around the knee-axis. On the right figure, you can see the positioning of the foot in relation to the force plate. The force plate can move upwards to simulate the ground reaction forces. In total, nine tendons of the major lower limb muscles are attached to pneumatic actuators to simulate the muscles forces during the stance phase of gait.

Figure B: Trapdoor with an inversion angle of 15 degrees. The trapdoor tilted from the moment the foot touched the plate during initial heel contact.

ROM inversion-eversion				
	ATFL rupture	ATFL-CFL rupture	ATFL-CFL reconstruction	ATFL reconstruction
Tibiotalar joint	1.7166	2.7802	1.054	2.8169
Talocalcaneal joint	1.057	4.1368	3.7432	3.5441
Tibiocalcaneal joint	-1.1637	-0.4756	-0.8633	-0.4865
Talonavicular joint	1.7088	-1.2422	-2.2849	2.6787
Calcaneocuboid joint	-1.0017	-0.7014	0.0948	-2.1207

Table 1: Change in ROM compared to intact ROM (in degrees). A positive value indicates an increased ROM compared to intact.

AA inversion-eversion				
	ATFL rupture	ATFL-CFL rupture	ATFL-CFL reconstruction	ATFL reconstruction
Tibiotalar joint	0.4808	3.1606	0.3355	3.592
Talocalcaneal joint	-3.3566	-3.8027	-1.9446	-5
Tibiocalcaneal joint	0.4267	0.3821	0.9454	1.0303
Talonavicular joint	-0.7686	1.7578	1.7805	1.8487
Calcaneocuboid joint	-4.9154	0.8797	-9.6531	-12.1934

Table 2: Change in AA compared to intact AA (degrees). A positive value indicates an increased eversion compared to intact.

ROM internal-external rotation				
	ATFL rupture	ATFL-CFL rupture	ATFL-CFL reconstruction	ATFL reconstruction
Tibiotalar joint	0.8691	0.3316	-1.2858	-0.3566
Talocalcaneal joint	2.4947	5.0423	4.9244	2.704
Tibiocalcaneal joint	-0.9995	-0.7048	-1.4352	-1.0608
Talonavicular joint	0.9563	-0.7466	-0.8818	0.3687
Calcaneocuboid joint	0.6003	-2.0201	2.6679	2.7877

Table 3: Change in ROM compared to intact ROM (in degrees). A positive value indicates an increased ROM compared to intact.

AA internal-external rotation				
	ATFL rupture	ATFL-CFL rupture	ATFL-CFL reconstruction	ATFL reconstruction
Tibiotalar joint	2.2134	1.0649	0.8291	0.054
Talocalcaneal joint	2.6388	-1.3988	0.7365	3.5945
Tibiocalcaneal joint	1.8513	1.7902	2.4645	4.6826
Talonavicular joint	3.2385	1.5919	1.2857	0.5767
Calcaneocuboid joint	1.0592	6.1028	-2.2911	0.9086

Table 4: Change in AA compared to intact AA (degrees). A positive value indicates an increased external rotation compared to intact.

ROM dorsi-plantar flexion				
	ATFL rupture	ATFL-CFL rupture	ATFL-CFL reconstruction	ATFL reconstruction
Tibiotalar joint	-4.3107	-4.9243	-7.2924	-5.6269
Talocalcaneal joint	-0.9261	-0.1578	-1.2958	-0.9528
Tibiocalcaneal joint	-5.5371	-1.7007	-2.2951	-3.8808
Talonavicular joint	1.4752	0.5482	-0.023	6.8187
Calcaneocuboid joint	2.0595	2.269	3.3546	7.4671

Table 5: Change in ROM compared to intact ROM (in degrees). A positive value indicates an increased ROM compared to intact.

AA dorsi-plantar flexion				
	ATFL rupture	ATFL-CFL rupture	ATFL-CFL reconstruction	ATFL reconstruction
Tibiotalar joint	-5.8938	-6.8849	-9.077	-5.82
Talocalcaneal joint	-0.9584	-0.0629	-1.7792	-3.7018
Tibiocalcaneal joint	-3.6957	-2.3248	-1.2588	1.6075
Talonavicular joint	-3.186	-0.6389	-2.2595	2.7133
Calcaneocuboid joint	2.9444	-8.0858	-12.7443	-2.0267

Table 6: Change in AA compared to intact AA (degrees). A positive value indicates an increased plantar flexion compared to intact.

ROM			
	inversion-eversion	internal-external rotation	dorsi-plantar flexion
Tibiotalar joint	2.0334	0.6838	-5.1892
Talocalcaneal joint	2.4947	3.0197	-0.0645
Tibiocalcaneal joint	-0.863	-0.0102	-3.3444
Talonavicular joint	0.9679	-0.3221	-4.3444
Calcaneocuboid joint	-0.6921	0.6681	2.6735

Table 7: Change in ROM during inverted walking compared to ROM during intact walking (degrees). A positive value indicates an increased ROM compared to intact.

AA			
	inversion-eversion	internal-external rotation	dorsi-plantar flexion
Tibiotalar joint	1.5119	1.3994	-4.1219
Talocalcaneal joint	-3.1016	1.5441	-1.5515
Tibiocalcaneal joint	0.4026	2.6837	-1.0868
Talonavicular joint	1.7544	1.6425	2.7849
Calcaneocuboid joint	-5.7853	2.1312	-2.7544

Table 8: Change in AA during inverted walking compared to AA during intact walking (degrees). A positive value indicates an increased eversion, external rotation and plantar flexion compared to intact.

ROM intact			
	inversion-eversion	internal-external rotation	dorsi-plantar flexion
Tibiotalar joint	5.6602	5.0656	9.4147
Talocalcaneal joint	6.0179	5.9266	10.2769
Tibiocalcaneal joint	5.3681	6.3120	20.0189
Talonavicular joint	8.4233	11.5056	22.9914
Calcaneocuboid joint	9.6049	7.3140	7.9136

Table 9: The ROM during the intact condition (in degrees) for the five joints and the three movement directions.

AA intact			
	inversion-eversion	internal-external rotation	dorsi-plantar flexion
Tibiotalar joint	6.7212	6.1137	14.7875
Talocalcaneal joint	-1.8094	-5.0661	5.9249
Tibiocalcaneal joint	2.5425	5.4440	10.0665
Talonavicular joint	-1.2518	-9.7224	11.9079
Calcaneocuboid joint	-6.8053	-4.6205	2.9487

Table 10: The AA during the intact condition (in degrees) for the five joints and the three movement directions. A positive value indicates eversion, external rotation and dorsiflexion.