Augmented Ligament Reconstruction Partially Restores Hindfoot and Midfoot Kinematics After Lateral Ligament Ruptures

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Background: Altered kinematics and persisting ankle instability have been associated with degenerative changes and osteochondral lesions.

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

Study Design: Controlled laboratory study.

Methods: Five fresh-frozen cadaveric specimens were tested in a custom-built gait simulator in 5 different conditions: intact, ATFL rupture, ATFL-CFL rupture, ATFL-CFL reconstruction, and ATFL reconstruction. For each condition, range of motion (ROM) and the average angle (AA) in the hindfoot and midfoot joints were calculated during the stance phase of normal and inverted gait.

Results: Ligament ruptures mainly changed ROM in the hindfoot and the AA in the hindfoot and midfoot and influenced the kinematics in all 3 movement directions. Combined ligament reconstruction was able to restore ROM in inversion-eversion in 4 of the 5 joints and ROM in internal-external rotation and dorsiflexion-plantarflexion in 3 of the 5 joints. It was also able to restore the AA in inversion-eversion in 2 of the 5 joints, the AA in internal-external rotation in all joints, and the AA in dorsiflexion-plantarflexion in 1 of the joints. Isolated ATFL reconstruction was able to restore ROM in inversion-eversion and internal-external rotation in 3 of the 5 joints and ROM in dorsiflexion-plantarflexion in 2 of the 5 joints. Isolated reconstruction was also able to restore the AA in inversion-eversion and dorsiflexion-plantarflexion in 2 of the joints and the AA in internal-external rotation in 3 of the joints. Both isolated reconstruction and combined reconstruction were most successful in restoring motion in the tibiocalcaneal and talonavicular joints and least successful in restoring motion in the talocalcaneal joint. However, combined reconstruction was still better at restoring motion in the talocalcaneal joint than isolated reconstruction (1/3 for ROM and 1/3 for the AA with isolated reconstruction compared to 1/3 for ROM and 2/3 for the AA with combined reconstruction).

Conclusion: Combined ATFL-CFL reconstruction showed better restored motion immediately after surgery than isolated ATFL reconstruction after a combined ATFL-CFL rupture.

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

Keywords: lateral ligament reconstruction; foot-ankle kinematics; ligament rupture; gait simulation

Ankle sprain is one of the most frequently treated musculoskeletal injuries, with a high incidence in the general population and during sports activities.[35,37] Although ankle sprains can occur during inversion, eversion, or hyperdorsiflexion of the foot, 85% of the sprains result from inversion trauma of the foot, rupturing the anterior talofibular ligament (ATFL) in 85% of the cases.[9] An additional rupture of the calcaneofibular ligament (CFL) is less frequent (20% of patients).[2] After an ankle sprain, a short time of immobilization may be helpful in relieving pain and swelling.[34,37] However, patients benefit most from using bracing and taping in combination with an exercise program to improve ankle stability.[33,37] Although ankle sprains are frequently considered minor injuries, they are painful and limit weightbearing activities. In addition, 30% to 50% of patients[8,20,28] will have persistent symptoms (eg, ankle instability, swelling, or recurrent ankle sprains) after the first weeks of nonoperative treatment. Those persistent symptoms can lead to secondary

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problems such as chronic ankle instability, altered ankle kinematics,[5] chondral injuries,[31] and ankle osteoarthritis.[32] In those patients and high-demand athletes, a surgical intervention is therefore considered.[1,33]

Of these, anatomic procedures are typically preferred over nonanatomic ones, as they are associated with more optimally restored anatomy, fewer complications (such as wound healing or nerve problems), easier surgical techniques, and better postoperative mobility.[3,18,27] The Broström technique is considered the "golden standard."[3] Although good postoperative subjective ankle stability is achieved,[30] this ligament restoration may not be strong enough to avoid sprain recurrence during physical activities.[12] Additionally, postoperative immobilization is required, which delays rehabilitation and can cause tissue degeneration.[25] Consequently, alternative or adapted surgery techniques based on the original Broström technique have been developed. One recent technique augments Broström repair with extra structural support such as suture tape.[24] As a result, the repaired ligament has higher loads to failure[36] and results in good subjective ankle stability.[6]

Suture tape augmentation also has been shown to improve the mean postoperative American Orthopaedic Foot & Ankle Society (AOFAS) score and result in faster improvement of the AOFAS score compared with Broström-Gould repair without suture tape augmentation.[39] However, to our knowledge, the ability of surgery with suture tape augmentation to restore foot-ankle kinematics during gait has not been studied previously. This is important because previous studies showed that altered kinematics and sustained ankle instability can lead to degenerative changes and osteochondral lesions.[23,32]

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

METHODS

Cadaveric Specimens

Five fresh-frozen lower leg cadaveric specimens without a history of major foot and ankle abnormalities were obtained via Science Care and amputated midtibially. These specimens were tested in 5 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 isolated reconstruction of the ATFL but resected CFL.

Ligament Resection and Surgical Reconstruction

All procedures were performed by an experienced orthopaedic surgeon (S.V.) while the specimen was attached to the gait simulator.[16] Standard instrumentation and techniques representative of the clinical setting were used. First, an anterolateral incision of 4 cm was made at the anterior border of the lateral malleolus and sinus tarsi, where lateral arthrotomy was performed to visualize 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 ATFL reconstruction, a 3.5-mm 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 3.5-mm tap, and a loaded suture anchor (3.5-mm SwiveLock biocomposite anchor; Arthrex) was inserted with 2 bundles of suture tape (InternalBrace; Arthrex). At the talar neck, around 1 cm anterior and superior to the sinus tarsi, a 4.75-mm drill hole (45° posteromedially) was made at the anatomic insertion of the ATFL. The talar tunnel was tapped with a 4.75-mm tap, and 1 of the suture tape bundles was inserted into the talar tunnel and fixed with another suture anchor (4.5 mm). The second bundle of suture tape was positioned underneath the peroneal tendons. Finally, a 3.5-mm drill hole (inferiorly and posteriorly) was made in the lateral wall of the calcaneus over the CFL anatomic insertion and was tapped with a 3.5-mm tap. Afterward, the second bundle was fixed with a third knotless suture anchor (3.5 mm) (Figure 1).

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

Gait Simulator and In Vitro Foot Bone Kinematics Calculation

For the in vitro tests, the specimens were attached to a custom-built gait simulator (see Appendix Figure A1, available in the online version of this article). Within this

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Figure 1. Schematic representation of ligament reconstruction procedures. The light grey zones are the drill direction of the holes. The dark grey lines indicate the positioning of the suture tape.

simulator, cadaveric specimens were tested dynamically by applying muscle forces representative of the stance phase of gait using pneumatic actuators attached to the tendons of 6 muscle groups (tibialis anterior + extensor hallucis longus + extensor digitorum longus, peroneus longus + peroneus brevis, gastrocnemius + soleus, tibialis posterior, flexor hallucis longus, flexor digitorum longus). Anterior displacement and flexion-extension around the knee axis were induced by electric servomotors, and the ground-reaction forces were simulated by upward movement of the force plate controlled by induced movement of the foot and ankle. This setup has been previously validated and described in the literature.[4,16,17,21]

Each foot was tested in 2 modalities, for which a set of 10 measurements was performed: First, normal overground gait was simulated, similar to published work.[4,16,17,21] Second, inversion was enforced during gait using a trapdoor that induced an inclination of 15° on the floor surface (see Appendix Figure A2, available online). The trapdoor was used to create a more challenging condition and is described in a study by Nieuwenhuijzen et al.[19]

Hindfoot kinematics was measured using 3D motion capture (accuracy, 90 μm; sampling frequency, 100 Hz) (Krypton; Metrix). A bone pin was inserted in the tibia, talus, calcaneus, cuboid, and navicular. On these pins, a cluster of 4 light-emitting diode (LED) markers was placed. The 3D position of the LED markers (measured by 3D motion capture) was combined with computed tomography–based information to calculate the 3D bone relative angles. Inversion-eversion was defined as movement around the anterior-posterior axis, internal-external rotation as movement around the proximal-distal axis, and dorsiflexion-plantarflexion as movement around the medial-lateral axis. The calculated angles were filtered with a 6-Hz low-pass filter (Matlab; MathWorks).

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

Statistical Analysis

Statistical analysis was performed using Matlab. A generalized 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 ROM and the AA in the 5 different joints. A variable intercept was used to correct for differences in intact walking between specimens (random effect). A fixed-effects model was included for the conditions and measurement types (normal walking and trapdoor walking), and a random-effects model for the different specimens was included. For all tests, the significance level was set at $\alpha = .05$.

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

RESULTS

Influence of Ligament Ruptures and Ligament Reconstruction

Isolated ATFL Rupture. An isolated ATFL rupture increased ROM in inversion-eversion in the tibiotalar (+21.52%; P = .003) and talonavicular joints (+32.55%; P < .001) (Figure 3A), increased ROM in internal-external rotation in the talocalcaneal joint (+67.14%; P = .017) (Figure 4A), but decreased ROM in dorsiflexion-plantarflexion in the tibiotalar (–10.60%; P < .001) and tibiocalcaneal joints (–15.54%; P < .001) (Figure 5A). Additionally, an isolated ATFL rupture increased the AA in external rotation (Figure 4B) and dorsiflexion (Figure 5B) in the tibiotalar (+15.93% external rotation and +40.03% dorsiflexion; P < .001) and talonavicular joints (+138.37% external rotation

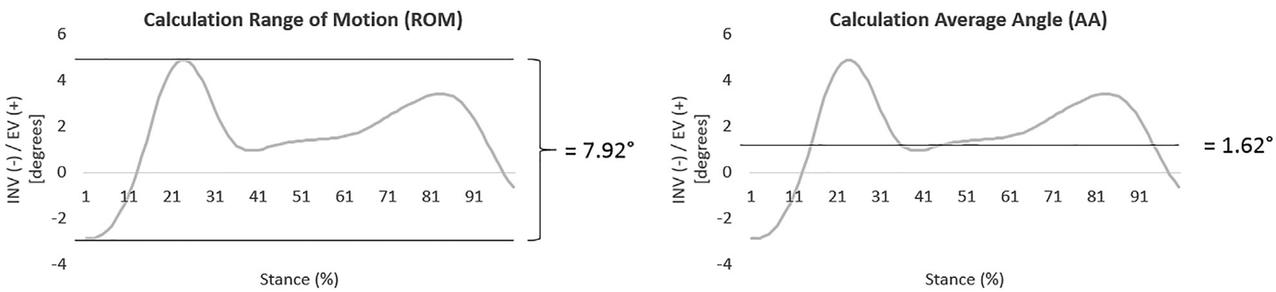

Figure 2. Calculation of range of motion (ROM) defined as the difference (in degrees) between the 2 extreme joint positions and calculation of the average angle (AA) as the mean value over the stance phase of gait. INV, inversion; EV, eversion.

and +40.80% dorsiflexion; $P < .001$), the AA in external rotation in the talocalcaneal joint (+74.51%; $P = .043$) (Figure 4B), the AA in dorsiflexion in the tibiocalcaneal joint (+109.70%; $P < .001$) (Figure 5B), and the AA in plantarflexion in the calcaneocuboid joint (+36.41%; $P = .039$) (Figure 5B).

Combined ATFL-CFL Rupture. A combined ATFL-CFL rupture increased even more ROM in inversion-eversion in the tibiotalar (+49.96%; $P < .001$) (Figure 3A) and talocalcaneal joints (+73.35%; $P < .001$) (Figure 3A) and ROM in internal-external rotation in the talocalcaneal joint (+86.56%; $P = .017$) (Figure 4A). Additionally, a combined rupture decreased ROM in dorsiflexion-plantarflexion in the tibiotalar joint (–33.03%; $P = .002$) but increased it in the calcaneocuboid joint (+14.21%; $P < .001$) (Figure 5A). A combined rupture also increased the AA in eversion in the tibiotalar (+354.74%; $P < .001$) and talonavicular joints (+9.54%; $P = .007$) (Figure 3B), the AA in inversion in the talocalcaneal joint (+101.31%; $P < .001$) (Figure 3B), and the AA in dorsiflexion in the tibiotalar joint (+56.12%; $P < .001$) (Figure 5B).

Isolated ATFL Reconstruction. There was no significant difference between isolated ATFL reconstruction and the intact condition for ROM in inversion-eversion in the talonavicular joint ($P = .193$) (Figure 3A), the AA in internal-external rotation in the tibiotalar ($P = .07$) and talonavicular joints ($P = .36$) (Figure 4B), and the AA in dorsiflexion-plantarflexion in the tibiocalcaneal ($P = .095$) and calcaneocuboid joints ($P = .517$) (Figure 5B). There was a significant difference between isolated ATFL reconstruction and the intact condition for ROM in inversion-eversion in the tibiotalar joint (+30.36%; $P < .001$) (Figure 3A) and ROM in dorsiflexion-plantarflexion in the tibiotalar (–40.71%; $P < .001$), tibiocalcaneal (–32.89%; $P < .001$), and calcaneocuboid joints (+105.31%; $P < .001$) (Figure 5A). There was also a significant difference between isolated ATFL reconstruction and the intact condition for the AA in inversion-eversion in the tibiotalar (+269.24% to eversion; $P < .001$), talocalcaneal (+84.15% to inversion; $P < .001$), and calcaneocuboid joints (+40.88% to inversion; $P < .001$) (Figure 3B) and the AA in dorsiflexion-plantarflexion in the talocalcaneal (+62.23% to dorsiflexion; $P < .001$) and talonavicular joints (+4.72% to dorsiflexion; $P < .001$) (Figure 5B). Isolated reconstruction even resulted in additional increased ROM in internal-external rotation in the calcaneocuboid joint (+3.47%; $P < .001$) (Figure 4A), increased AA in external rotation in the tibiocalcaneal joint (+894.25%; $P = .002$) (Figure 4B), and increased AA in dorsiflexion in the talocalcaneal joint (+62.23%; $P < .001$) (Figure 5B).

Combined ATFL-CFL Reconstruction. There was no significant difference compared with the intact condition for ROM in inversion-eversion in the tibiotalar ($P = .333$) and talonavicular joints ($P = .07$) (Figure 3A) and ROM in dorsiflexion-plantarflexion in the tibiocalcaneal joint ($P = .49$) (Figure 5A). There was also no significant difference in the AA in inversion-eversion in the tibiotalar joint ($P = .942$) (Figure 3B), the AA in internal-external rotation in the tibiotalar ($P = .28$) and talocalcaneal joints ($P = .11$) (Figure 4B), and the AA in dorsiflexion-plantarflexion in the tibiocalcaneal joint ($P = .11$) (Figure 5B) compared with intact walking. There was a significant difference between combined reconstruction and the intact condition for ROM in inversion-eversion ($P = .023$) (Figure 3A) and internal-external rotation ($P = .002$) (Figure 4A) in the talocalcaneal joint (+59.16% inversion-eversion and +62.53% internal-external rotation) and ROM in dorsiflexion-plantarflexion in the tibiotalar (–50.91%; $P < .001$) and calcaneocuboid joints (+60.96%; $P = .039$) (Figure 5A). There was also a significant difference between combined reconstruction and the intact condition for the AA in inversion-eversion (+168.50% to eversion; $P = .021$) (Figure 3B) and internal-external rotation (+126.65% to external rotation; $P = .04$) (Figure 4B) in the talonavicular joint and the AA in dorsiflexion-plantarflexion in the tibiotalar (+47.54% to dorsiflexion; $P < .001$), talocalcaneal (+1.92% to dorsiflexion; $P = .02$), talonavicular (+20.74% to dorsiflexion; $P < .001$), and calcaneocuboid joints (+280.23% to dorsiflexion; $P = .039$) (Figure 5B). Combined reconstruction additionally increased the AA in inversion in the calcaneocuboid joint (+238.83%; $P < .001$) (Figure 3B).

Influence of Trapdoor Walking

Walking on the trapdoor decreased ROM in dorsiflexion-plantarflexion in the tibiotalar joint (–16.02%; $P < .001$) and increased ROM in dorsiflexion-plantarflexion in the talonavicular joint (+17.21%; $P < .001$) compared with normal walking (Figure 6, left). The trapdoor increased the AA in external rotation in the tibiotalar (+17.67%; $P < .001$) and tibiocalcaneal joints (+43.88%; $P = .03$) and the AA in

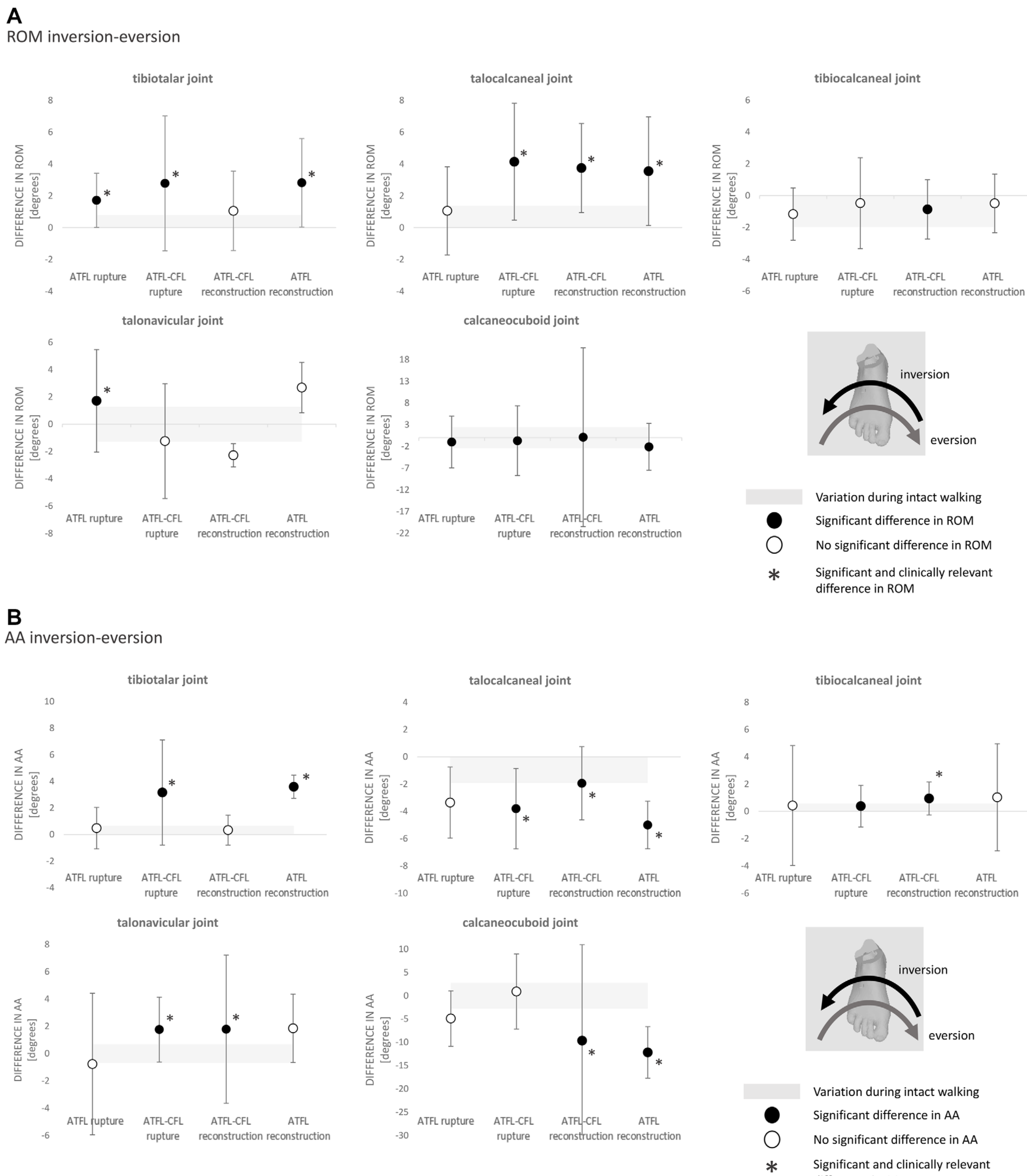

Figure 3. Mean difference and 95% CI for (A) range of motion (ROM) and (B) average angle (AA) compared with the intact condition in inversion-eversion. A positive value indicates (A) increased ROM or (B) increased eversion compared with the intact condition. The *y*-axis range is set at 12° for ROM and 14° for the AA, except for ROM and AA in the calcaneocuboid joint. ATFL, anterior talofibular ligament; CFL, calcaneofibular ligament.

dorsiflexion in the calcaneocuboid joint (+3.54%; P = .011) (Figure 6, right). The trapdoor did not change ROM or dynamic alignment in the other movement directions or joints (Figure 6).

DISCUSSION

In this study, the effect of individual and combined ligament ruptures (ATFL and ATFL + CFL) and reconstruction

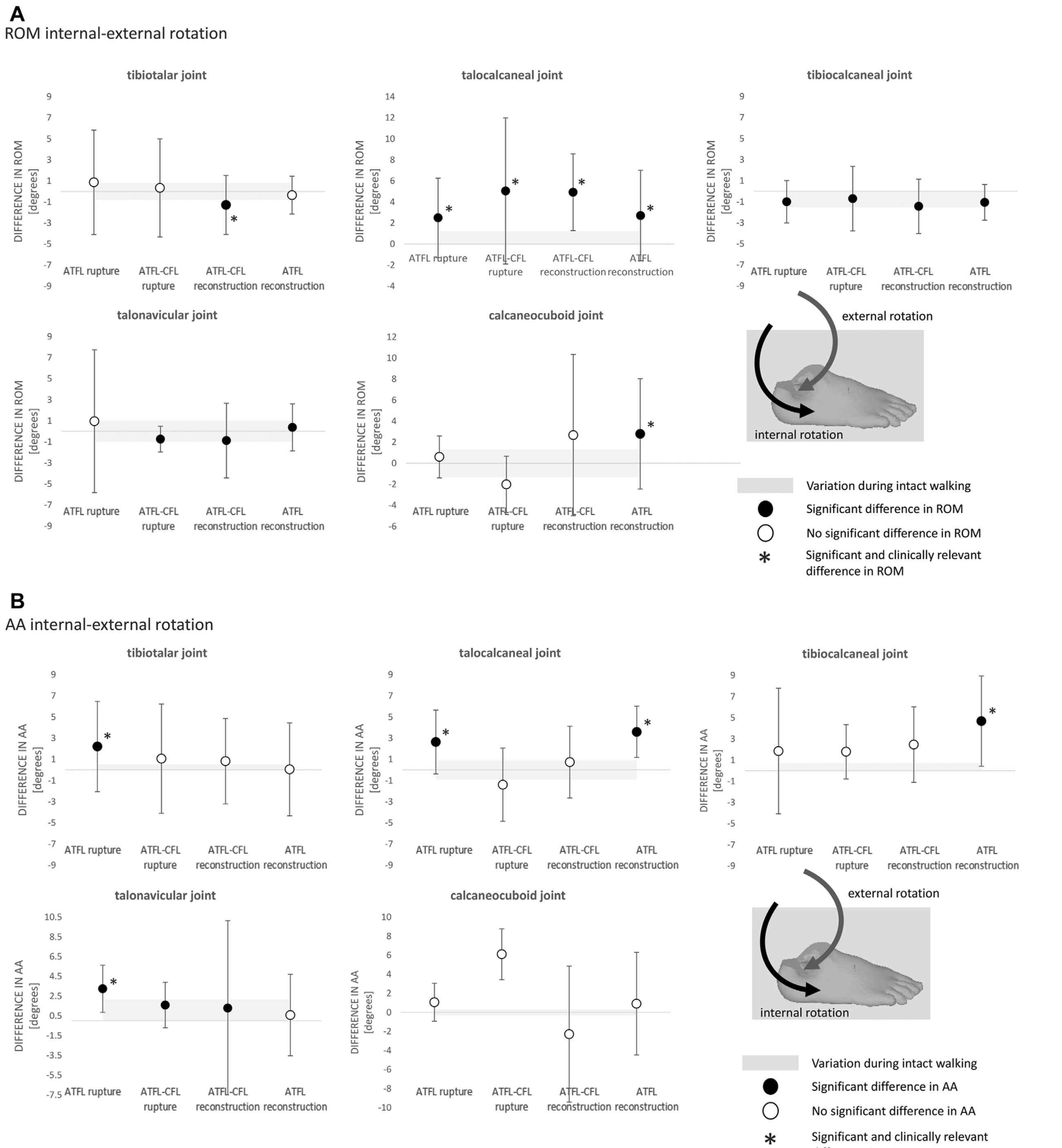

Figure 4. Mean difference and 95% CI for (A) range of motion (ROM) and (B) average angle (AA) compared with the intact condition in internal-external rotation. A positive value indicates (A) increased ROM or (B) increased external rotation compared with the intact condition. The y-axis range is set at 18° for both the ROM and the AA, except for AA in the calcaneocuboid joint. ATFL, anterior talofibular ligament; CFL, calcaneofibular ligament.

(ATFL and ATFL + CFL) on kinematics during normal and inverted walking was evaluated based on movement excursion (ROM) and 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 aberrant kinematics caused by a ligament rupture, we conclude that suture tape augmentation is efficient in restoring hindfoot and midfoot

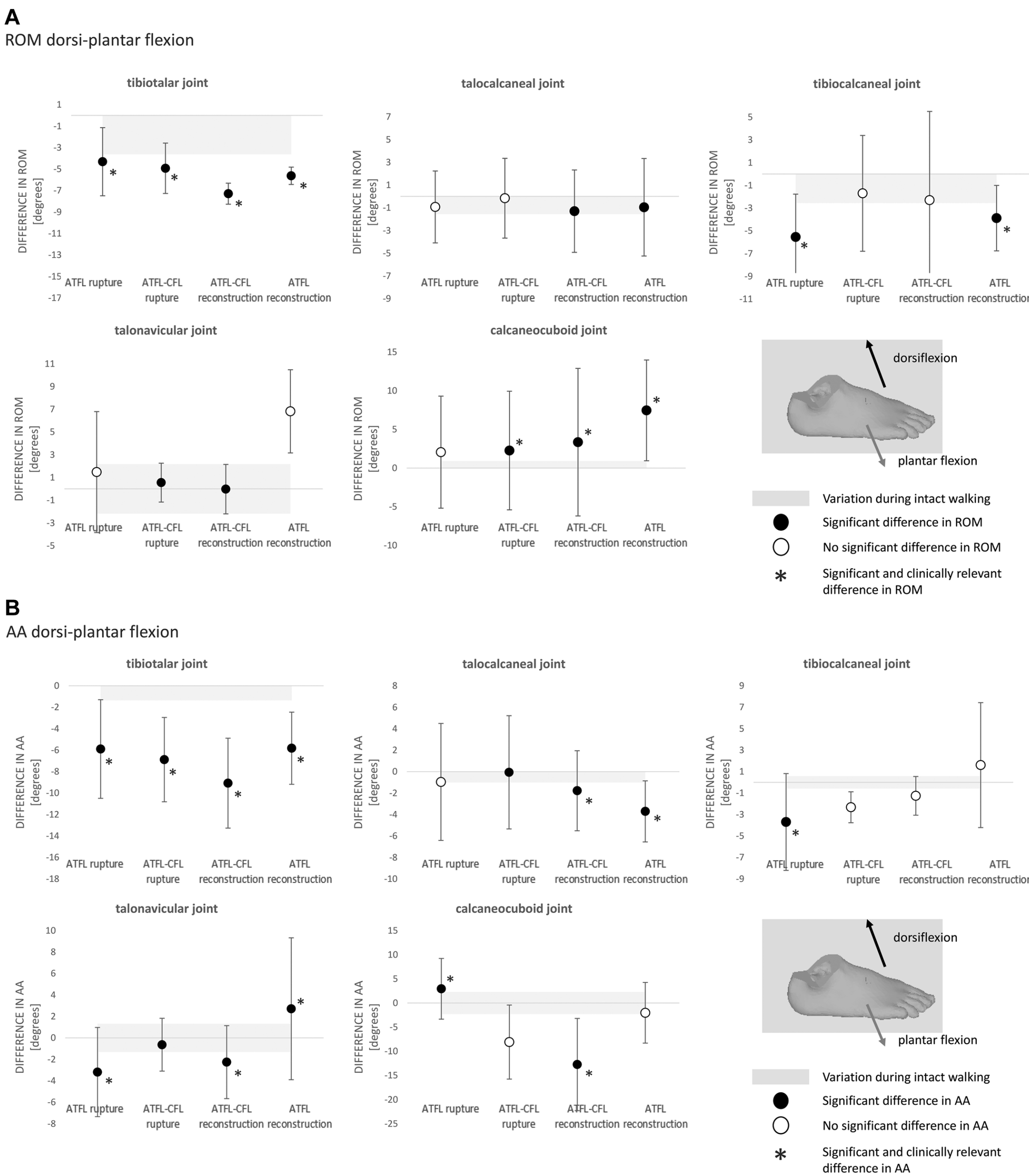

Figure 5. Mean difference and 95% CI for (A) range of motion (ROM) and (B) average angle (AA) compared with the intact condition in dorsiflexion-plantarflexion. A positive value indicates (A) increased ROM or (B) increased plantarflexion compared with the intact condition. The y-axis range is set at 17° for ROM and 18° for AA, except for ROM and AA in the calcaneocuboid joint. ATFL, anterior talofibular ligament; CFL, calcaneofibular ligament.

instability after ligament ruptures at the time of surgery. However, its effect on ligament healing remains unknown.

As expected based on anatomy, an isolated ATFL rupture increased ROM in inversion-eversion in the tibiotalar joint, while an additional CFL rupture increased ROM in inversion-eversion even more and induced increased ROM in inversion-eversion and an excessive AA in inversion in the talocalcaneal joint. These latter changes are in

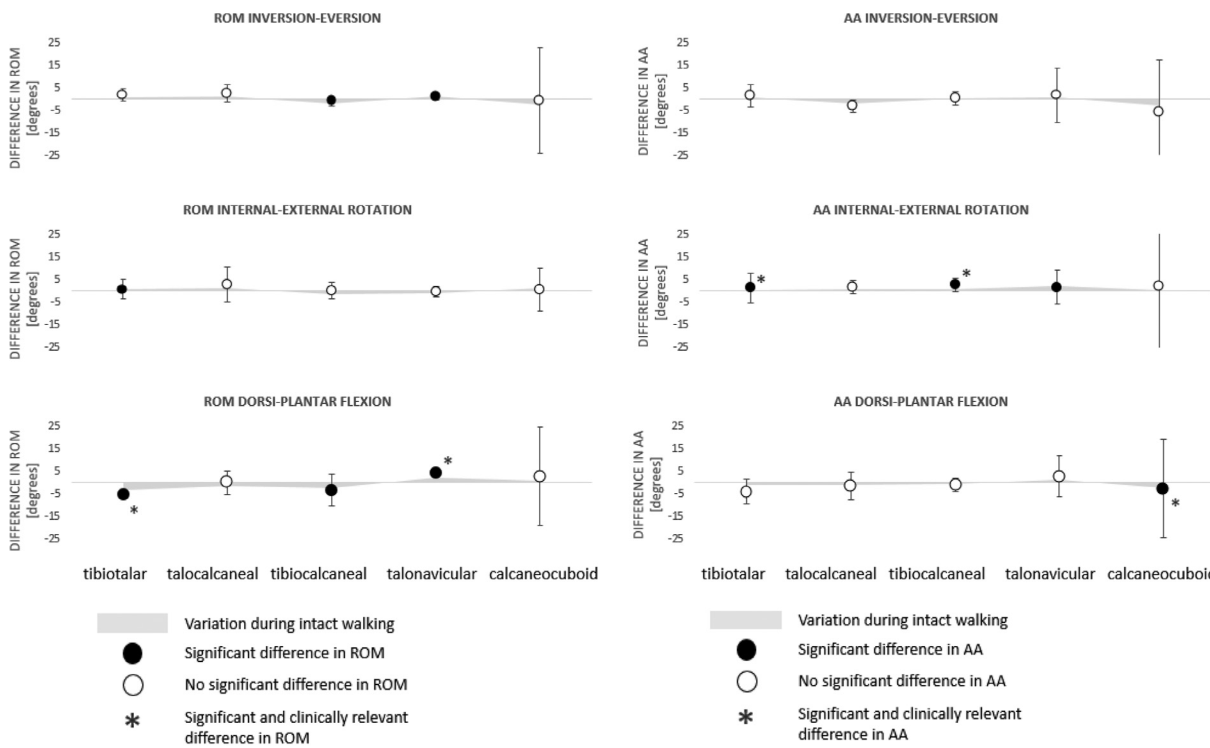

Figure 6. Mean difference and 95% CI for (left) range of motion (ROM) and (right) average angle (AA) during inverted walking compared with normal walking in the 3 movement directions. A positive value indicates (left) increased ROM or (right) increased eversion, external rotation, and plantarflexion compared with normal walking. The y-axis range is set at 50° for ROM and AA.

accordance with the anatomic position of the CFL, being the only ligament covering both the tibiotalar and talocalcaneal joints.[14] Consequently, for a combined ATFL-CFL rupture, only combined ATFL-CFL reconstruction was able to fully restore altered kinematics in the tibiotalar joint and partially restore changes in the talocalcaneal joint, whereas isolated ATFL reconstruction was ineffective in restoring tibiocalcaneal frontal-plane kinematics.

A lateral ligament rupture not only changed frontal-plane kinematics but also transverse-plane kinematics. An isolated ATFL rupture increased ROM in internal-external rotation in the talocalcaneal joint, and an additional CFL rupture further increased this ROM. In contrast to the frontal plane, neither of the ligament reconstruction procedures was able to completely restore transverse-plane kinematic changes.

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

Overall, after a combined ATFL-CFL rupture, combined ATFL-CFL reconstruction better restored normal motion than isolated ATFL reconstruction, especially for frontal-plane ROM and AA. This is in contrast with the study of Pereira et al[22] in which no significant differences were found in the kinematics after both isolated and combined ligament reconstruction. However, in Pereira et al's study[22] the cadaveric specimens were subjected to an inversion of 20°, which is more challenging than the normal and trapdoor gait that were investigated in this study. Although surgeons think that combined reconstruction may benefit patients, CFL reconstruction surgery is not always considered, given its location underneath the peroneal tendons, close to the sural nerve.[26] It is therefore still questionable if the potential benefits of additional CFL repair and augmentation outweigh these risks.

It needs to be considered that ligament reconstruction surgery performed in vitro differs from ligament surgery performed in vivo. In the clinic, the surgeon first repairs the original ligament with the Broström-Gould procedure and afterward augments this repair with suture tape. In this study, only ligament reconstruction with suture tape was performed. The findings of this study indicate that ligament reconstruction with suture tape is able to restore ROM to physiological values in the hindfoot and midfoot joints as well as to partially restore dynamic foot alignment. Consequently, ligament reconstruction using suture tape could potentially protect the repaired ligament against stretching during the healing process and possibly allow faster rehabilitation. Additionally, previous studies showed decreased performance of Broström repair after several years by stretching the repaired ligament.[12] Suture tape augmentation might be able to prevent this by decreasing the stretch on the repaired ligament from the beginning.

An assessment of lateral ligament reconstruction procedures cannot be limited to evaluating hindfoot kinematics in isolation but should include an examination of midfoot kinematics because a lateral ligament rupture changes hindfoot and midfoot kinematics. Previous in vitro and in vivo studies used the anterior drawer and talar tilt tests to evaluate the success of ligament surgery, thereby only evaluating the tibiotalar and talocalcaneal joints in inversion-eversion and dorsiflexion-plantarflexion.[7,38] With the in vitro setup used in this study, the effect of ATFL and CFL ruptures on midfoot kinematics was confirmed: An ATFL rupture increased ROM in inversion-eversion in the talonavicular joint, increased the AA in external rotation and dorsiflexion in the talonavicular joint, and increased the AA in plantarflexion in the calcaneocuboid joint. A combined ATFL-CFL rupture further increased ROM in dorsiflexion-plantarflexion in the calcaneocuboid joint and increased the AA in eversion in the talonavicular joint. A midfoot evaluation is particularly important to assess the risk of ligament overtightening. Indeed, compensatory changes in midfoot kinematics were found after ligament surgery: Combined reconstruction increased the AA in inversion in the calcaneocuboid joint, whereas isolated ATFL reconstruction increased the ROM in internal-external rotation in the calcaneocuboid joint.

A trapdoor was used to evaluate the effect of ligament ruptures and consequent ligament reconstruction in more challenging conditions. The trapdoor was previously used to simulate a lateral ankle sprain.[19] However, only slight differences in kinematics were observed during trapdoor walking compared with normal walking. Yet, to protect the integrity of the cadaveric specimens, the trapdoor only tilted 15° at heel strike, whereas typically a tilt of 25° is used in patients with chronic ankle instability[19] in vivo.

There are several limitations associated with this in vitro study. First, although we did impose muscle forces representative of the stance phase of normal gait, the role of the intrinsic foot musculature and proprioceptive responses due to neuromuscular control after inversion were disregarded. Studies showed changes in peroneus longus, tibialis anterior, rectus femoris, and gluteus medius muscles in patients with chronic ankle instability and in healthy volunteers during increased inversion angles.[10,19] Therefore, the role of muscle activation in ankle stabilization was not investigated in our cadaveric setup, and only the isolated effect of ligament ruptures and consequent reconstruction on hindfoot and midfoot kinematics during the stance phase of gait can be studied. Second, the natural healing process cannot be taken into account. However, this study showed that ligament reconstruction with suture tape augmentation is able to protect Broström-Gould repair at the time of surgery. Third, the changes in kinematics after ligament ruptures in this study, especially in internal-external rotation, do not fully match the findings in the literature.[11,15] However, these changes in internal-external rotation were mainly captured in the talocalcaneal joint, whereas in vivo studies report changes in tibiocalcaneal alignment and cannot isolate movements between the tibiotalar and talocalcaneal joints. Fourth, the mean age of the specimens was relatively high (77.8 years, ranging between 53 and 82 years) and might not be a good representation of the young population in which Broström repair is typically performed.[13,29,36] Indeed, the soft tissue quality might be affected because of the age of the donors, but the use of cadaveric samples allowed us to study the influence of ligament ruptures and reconstruction on individual foot bone motion, which cannot be measured in in vivo studies. Finally, this study was underpowered to detect all of the differences because only 5 cadaveric specimens were measured.

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

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REFERENCES

1. Acevedo JI, Ortiz C, Golano P, Nery C. ArthroBroström lateral ankle stabilization technique: an anatomic study. *Am J Sports Med*. 2015;43(10):2564-2571.
2. Broström L. Sprained ankles, I: anatomic lesions in recent sprains. *Acta Chir Scand*. 1964;128:483-495.
3. Buerer Y, Winkler M, Burn A, Chopra S, Crevoisier X. Evaluation of a modified Broström-Gould procedure for treatment of chronic lateral ankle instability: a retrospective study with critical analysis of outcome scoring. *Foot Ankle Surg*. 2013;19(1):36-41.
4. Burg J, Peeters K, Natsakis T, Dereymaeker G, Vander Sloten J, Jonkers I. In vitro analysis of muscle activity illustrates mediolateral decoupling of hind and mid foot bone motion. *Gait Posture*. 2013;38(1):56-61.
5. Caputo AM, Lee JY, Spritzer CE, et al. In vivo kinematics of the tibiotalar joint after lateral ankle instability. *Am J Sports Med*. 2009;37(11):2241-2248.
6. Cho B-K, Park K-J, Kim S-W, Lee H-J, Choi S-M. Minimal invasive suture-tape augmentation for chronic ankle instability. *Foot Ankle Int*. 2015;36(11):1330-1338.
7. Drakos MC, Behrens SB, Paller D, Murphy C, DiGiovanni CW. Biomechanical comparison of an open vs arthroscopic approach for lateral ankle instability. *Foot Ankle Int*. 2014;35(8):809-815.
8. Gerber J, Williams G, Scoville C, Arciero R, Taylor D. Persistent disability associated with ankle sprains: a prospective examination of an athletic population. *Foot Ankle Int*. 1998;19(10):653-660.
9. Golanó P, Vega J, de Leeuw PAJ, et al. Anatomy of the ankle ligaments: a pictorial essay. *Knee Surg Sports Traumatol Arthrosc*. 2010;18(5):557-569.
10. Konradsen L, Voigt M, Hojsgaard C. Ankle inversion: the role of the dynamic injuries defense mechanism. *Am J Sports Med*. 1997;25(1):54-58.
11. Liu K, Uygur M, Kaminski T. Effect of ankle instability on gait parameters: a systematic review. *Athl Train Sports Health Care*. 2012;4(6):275-281.

12. Maffulli N, Del Buono A, Maffulli GD, et al. Isolated anterior talofibular ligament Broström repair for chronic lateral ankle instability: 9-year follow-up. *Am J Sports Med*. 2013;41(4):858-864.
13. Maffulli N, Ferran NA. Management of acute and chronic ankle instability. *J Am Acad Orthop Surg*. 2008;16(10):608-615.
14. Matsui K, Takao M, Tochigi Y, Ozeki S, Glazebrook M. Anatomy of anterior talofibular ligament and calcaneofibular ligament for minimally invasive surgery: a systematic review. *Knee Surg Sports Traumatol Arthrosc*. 2017;25(6):1892-1902.
15. Moisan G, Descarreaux M, Cantin V. Effects of chronic ankle instability on kinetics, kinematics and muscle activity during walking and running: a systematic review. *Gait Posture*. 2017;52(1):381-399.
16. Natsakis T, Burg J, Dereymaeker G, Jonkers I, Vander Sloten J. Inertial control as novel technique for in vitro gait simulations. *J Biomech*. 2015;48(2):392-395.
17. Natsakis T, Burg J, Dereymaeker G, Vander Sloten J, Jonkers I. Extrinsic muscle forces affect ankle loading before and after total ankle arthroplasty. *Clin Orthop Relat Res*. 2015;473(9):3028-3037.
18. Ng ZD, Das De S. Modified Broström-Evans-Gould technique for recurrent lateral ankle ligament instability. *J Orthop Surg*. 2007;15(3):306-310.
19. Nieuwenhuijzen PHJA, Gruneberg C, Duysens J. Mechanically induced ankle inversion during human walking and jumping. *J Neurosci Methods*. 2002;117:133-140.
20. Palmer-Green D, Batt M, Scammell B. Simple advice for a simple ankle sprain? The not so benign ankle injury. *Osteoarthritis Cartilage*. 2016;24(6):947-948.
21. Peeters K, Natsakis T, Burg F, et al. An in vitro approach to the evaluation of foot-ankle kinematics: performance evaluation of a custom-built gait simulator. *J Eng Med*. 2013;227(9):955-967.
22. Pereira HMD, D'Hooghe P, Anderson N, et al. Ankle and subtalar joint kinematics following lateral ligament repair - implications for early surgical treatment. *Arthroscopy*. 2017;33(10):e101.
23. Pihlajamäki H, Hietaniemi K, Paavola M, Visuri T, Mattila VM. Surgical versus functional treatment for acute ruptures of the lateral ligament complex of the ankle in young men. *J Bone Joint Surg Am*. 2010;92(14):2367-2374.
24. Prissel M, Roukis TS. All-inside, anatomical lateral ankle stabilization for revision and complex primary lateral ankle stabilization. *Foot Ankle Spec*. 2014;7(6):484-491.
25. Provenzano PP, Martinez DA, Grindeland RE, et al. Hindlimb unloading alters ligament healing. *J Appl Physiol*. 2003;94(1):314-324.
26. Riedl O, Frey M. Anatomy of the sural nerve: cadaver study and literature review. *Plast Reconstr Surg*. 2013;131(4):802-810.
27. Sammarco VJ. Complications of lateral ankle ligament reconstruction. *Clin Orthop Relat Res*. 2001;391:123-132.
28. Schaap GR, de Keizer G, Marti K. Inversion trauma of the ankle. *J Orthop Trauma Surg*. 1989;108(5):273-275.
29. Schenck RC, Coughlin MJ. Lateral ankle instability and revision surgery alternatives in the athlete. *Foot Ankle Clin*. 2009;14(2):205-214.
30. Shahrulazua A, Ariff Sukimin MS, Tengku Muzaffar TMS, Yusof MI. Early functional outcome of a modified Broström-Gould surgery using bioabsorbable suture anchor for chronic lateral ankle instability. *Singapore Med J*. 2010;51(3):235-241.
31. Sugimoto K, Takakura Y, Okahashi K, Samoto N, Kawate K, Iwai M. Chondral injuries of the ankle with recurrent lateral instability: an arthroscopic study. *J Bone Joint Surg Am*. 2009;91(1):99-106.
32. Valderrabano V, Hintermann B, Horisberger M, Shing Fung T. Ligamentous posttraumatic ankle osteoarthritis. *Am J Sports Med*. 2006;34(4):612-620.
33. van den Bekerom MPJ, Kerkhoffs GMMJ, McCollum GA, Calder JDF, van Dijk CN. Management of acute lateral ankle ligament injury in the athlete. *Knee Surg Sports Traumatol Arthrosc*. 2013;21(6):1390-1395.
34. van den Bekerom MPJ, Struijs PAA, Blankevoort L, Welling L, van Dijk CN, Kerkhoffs GMMJ. What is the evidence for rest, ice, compression, and elevation therapy in the treatment of ankle sprains in adults? *J Athl Train*. 2012;47(4):435-443.
35. van Ochten JM, van Middelkoop M, Meuffels D, Bierma-Zeinstra SM. Chronic complaints after ankle sprains: a systematic review on effectiveness of treatments. *J Orthop Sports Phys Ther*. 2014;44(11):862-871.
36. Viens NA, Wijdicks CA, Campbell KJ, LaPrade RF, Clanton TO. Anterior talofibular ligament ruptures, part 1: biomechanical comparison of augmented Broström repair techniques with the intact anterior talofibular ligament. *Am J Sports Med*. 2013;42(2):405-411.
37. Vuurberg G, Hoorntje A, Wink LM, et al. Diagnosis, treatment and prevention of ankle sprains: update of an evidence-based clinical guideline. *Br J Sports Med*. 2018;52(15):956.
38. Waldrop NE, Wijdicks CA, Jansson KS, LaPrade RF, Clanton TO. Anatomic suture anchor versus the Broström technique for anterior talofibular ligament repair: a biomechanical comparison. *Am J Sports Med*. 2012;40(11):2590-2596.
39. Yoo JS, Yang EA. Clinical results of an arthroscopic modified Broström operation with and without an internal brace. *J Orthop Traumatol*. 2016;17(4):353-360.