UNIVERSITAT DE BARCELONA

Lateral Ankle Instability: From Anatomy to Surgery

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4. Table of contents

5. Abbreviations and acronyms

- AB: Arthroscopic Brostrom
- ATIFL: Anterior Tibiofibular Ligament
- ATFL: Anterior talofibular ligament
- ATFLinf: ATFL’s inferior fascicle
- ATFLsup: ATFL’s superior fascicle
- CFL: Calcaneofibular ligament
- CAI: Chronic ankle instability
- IER: Inferior extensor retinaculum
- MCL: Medial collateral ligaments
- LCL: Lateral collateral ligaments
- LFTCL: Lateral fibulotalocalcaneal ligament complex
- PTFL: Posterior talofibular ligament
- PTIFL: Posterior tibiofibular ligament
- SPN: Superficial peroneal nerve

6. List of Articles in the Thesis

Thesis in a compendium of publications format.

This thesis consists of 4 objectives and 4 articles listed below:

1. Guelfi M, **Nunes GA**, Malagelada F, Cordier G, Dalmau-Pastor M, Vega J. Arthroscopic Assisted Versus All-Arthroscopic Ankle Stabilization Technique. Foot Ankle Int. 2020;41(11):1360-1367. Impact factor 2,827, Q2 in ORTHOPEDICS (32/82), 2020.
2. Cordier G, **Nunes GA**, Vega J, Roure F, Dalmau-Pastor M. Connecting fibers between the ATFL's inferior fascicle and CFL transmit tension between both ligaments. Knee Surgery, Sport Traumatol Arthrosc. March 2021:21-26. Impact factor 4,114, Q1 in SPORT SCIENCES (21/88), Q1 in SURGERY (40/213), Q1 in ORTHOPEDICS (17/86), 2021.
3. **Nunes GA**, Ferreira GF, Caetano RM, Mann TS, Guelfi M. All-inside arthroscopic anterior talofibular ligament repair: a case series. Int Orthop. 2022 Feb;46(2):273-279. Impact Factor 2,7, Q2 in ORTHOPEDICS (31/86)
4. **Nunes GA**, Martinez LM, Cordier G, Michels F, Vega J, Moreno RS, DalmauPastor M. The ATFL inferior fascicle, the CFL, and the PTFL have a continuous footprint on the medial side of the fibula. Knee Surg Sports Traumatol Arthrosc. 2023 Sep 2. Impact factor 3,3, Q1 in SPORT SCIENCES (19/127), Q1 in SURGERY (38/292), Q1 in ORTHOPEDICS (17/136), 2023.

7. Thesis Summary

Title: Lateral Ankle Instability: From Anatomy to Surgery

Introduction: Knowledge of the anatomy of the lateral ligaments of the ankle is essential for understanding their function, pathophysiology, and treatment options. Recently, new anatomical features have been described, including previously undescribed connections between these ligaments. Consequently, new concepts and anatomical techniques for the arthroscopic treatment of lesions in this area have emerged. However, these anatomical advances' applicability and mechanical role still need to be studied. Additionally, the clinical relevance of these anatomical concepts in the surgical field requires further exploration and investigation.

Hypothesis: The connections between the lateral collateral ligaments of the ankle extend to the medial facet of the fibula and have a biomechanical role. Based on new anatomical concepts, arthroscopic anatomical techniques used to repair the lateral ligaments of the ankle have good clinical and functional outcomes.

Objectives: This PhD thesis aims to conduct biomechanical and anatomical research on the lateral ligaments of the ankle and their connections and analyze the clinical outcomes of the arthroscopic anatomical techniques used to treat lateral ankle instability.

Methods: We performed two anatomical and two clinical studies. In the first anatomical study, 13 fresh-frozen below-the-knee ankle specimens were dissected in a protocolized manner until the lateral ligaments were exposed. A complete injury to the anterior talofibular ligament (ATFL) fascicles was created in the proximal third of the ligament. A specifically designed displacement transducer was fixed in the calcaneofibular ligament (CFL) and the calcaneus's lateral part. A traction was applied to the anterior talofibular ligament inferior fascicle (ATFL inf) while the transducer measured the lengthening that this force created in the CFL. In the second anatomical study, eleven fresh-frozen ankle specimens were dissected. The calcaneus, talus, and fibula were separated, maintaining the lateral ligament footprints. Subsequently, each bone was assessed by a white-structured-light scanner. The footprint areas of the talus, calcaneus, and fibula were studied, and the surface areas were quantified in cm2.

In the first clinical study, 39 patients were surgically treated for CAI using arthroscopic Brostrom (AB) and arthroscopic all-inside repair. Functional outcomes using the American Orthopaedic Foot & Ankle Society (AOFAS) hindfoot score and visual analog pain scale (VAS) were assessed pre- and postoperatively. Range of motion and complications were recorded. The results of both techniques were analyzed and compared. The second clinical study is a series of cases of 18 patients with CAI who underwent arthroscopic all-inside repair. The evaluation was made using the AOFAS, VAS, anterior drawer, and talar tilt tests. Range of motion and complications were recorded.

Results: In the first anatomical study, all examined specimens identified the fibers connecting the ATFLif and the CFL. The displacement transducer indicated lengthening of the CFL in all measurements, with a median lengthening of 0.59 mm (SD ± 0.34). In the subsequent anatomical investigation utilizing advanced bone scanning techniques, it was conclusively established that the ATFLif, CFL, and posterior talofibular ligament (PTFL) footprints are continuous along the medial aspect of the fibula. This analysis yielded a unified footprint area with a mean measurement of 4.8 cm^2 (± 0.7 cm^2). Notably, in 9 out of 11 feet assessed, the ATFL footprint on the talus consisted of two distinct portions, while a continuous insertion was observed in the remaining 2 feet. Furthermore, the CFL's insertion on the calcaneus was characterized as a singular footprint across all reviewed cases.

In the first clinical study, the AB group comprised 20 patients with a mean age of 30.2 (18-42) years and a mean follow-up of 19.6 (12-28) months. The arthroscopic all-inside repair group comprised 19 patients with a mean age of 30.9 (range, 18-46) years and a mean follow-up of 20.7 (range, 13-32) months. In both groups, the AOFAS and VAS scores significantly improved compared with preoperative values ($P < 0.001$), with no difference ($P > 0.001$) between groups. In the AB group, the mean AOFAS score improved from 67 (range, 44-87) to 92 (range, 76-100), and the mean VAS score from 6.4 (range, 3-10) to 1.2 (range, 0-3). In the AI group, the mean AOFAS score changed from 60 (range, 32-87) to 93 (range, 76-100), and the mean VAS score from 6.1 (range, 4-10) to 0.8 (range, 0-3). Eight complications (40%) were recorded at the final followup

in the AB group. In the arthroscopic all-inside repair group, one complication (5.3%) was observed ($P < .05$). The second clinical study analyzed 18 patients with a mean follow-up period of 12 months. There was an improvement in the AOFAS ($p < 0.001$), with the mean improving from 69.6 points to 98.1, standard deviation (SD) = 11.09, and in the mean VAS score ($p < 0.001$), from 5.0 to 0.5 points (SD = 0.78). All ankles were stable, as assessed by the anterior drawer and talar tilt tests. The only complication found was neurapraxia of the superficial fibular nerve in one patient (5%). All the patients classified the treatment as good or excellent and returned to sports activities without limitations.

Conclusions: The connecting fibers between the ATFLif and CFL are sufficiently strong to transfer tension from one structure to another. The ATFLif, CFL, and PTFL share a continuous footprint on the medial side of the fibula. Treating CAI with anatomic all-inside arthroscopic ATFL repair produces excellent functional and clinical outcomes with a low complication rate.

Resum de Tesi

Títol: Inestabilitat lateral del turmell: de l'anatomia a la cirurgia

Introducció: El coneixement de l'anatomia dels lligaments laterals del turmell és essencial per entendre la seva funció, fisiopatologia i opcions de tractament. Recentment, s'han descrit noves connexions i característiques d'aquests lligaments. En conseqüència, han sorgit nous conceptes i tècniques anatòmiques per al tractament artroscòpic de lesions en aquesta zona. No obstant això, l'aplicabilitat i el paper mecànic d'aquests avenços anatòmics romanen sense estudiar. A més, la rellevància clínica d'aquests conceptes anatòmics en l'àmbit quirúrgic requereix més exploració i investigació.

Hipòtesi: les connexions entre els lligaments col·laterals laterals del turmell s'estenen fins a la faceta medial del peroné, i tenen un paper biomecànic. A partir de nous conceptes anatòmics, les tècniques anatòmiques artroscòpiques utilitzades per reparar els lligaments laterals del turmell tenen bons resultats clínics i funcionals.

Objectius: Aquesta tesi doctoral pretén dur a terme investigacions biomecàniques i anatòmiques sobre els lligaments laterals del turmell i les seves connexions i analitzar els resultats clínics de les tècniques anatòmiques artroscòpiques utilitzades per tractar la inestabilitat lateral del turmell.

Mètodes: Hem realitzat dos estudis anatòmics i dos estudis clínics. En el primer estudi anatòmic, es van dissecar de manera protocol·litzada 13 espècimens de turmell fins que es van exposar els lligaments laterals. Es va crear una lesió completa als fascicles del lligament talofibular anterior (ATFL) al terç proximal del lligament. Es va fixar un transductor de desplaçament dissenyat específicament al lligament calcaneofibular (CFL) i a la part lateral del calcani. Es va aplicar una tracció al fascicle inferior del lligament talofibular anterior (ATFL inf) mentre el transductor mesurava l'allargament que aquesta força creava a la CFL. En el segon estudi anatòmic, es van dissecar onze exemplars de turmell frescos congelats. Es van separar el calcani, l'astràgal i el peroné, mantenint les àrees d'inserció laterals del lligament. Posteriorment, cada os

va ser avaluat per una màquina escàner de llum. Es van seleccionar les àrees d'inserció a l'astràgal, el calcani i el peroné, i les àrees superficials es van quantificar en cm2.

En el primer estudi clínic, 39 pacients van ser tractats quirúrgicament per CAI mitjançant Brostrom artroscòpic (AB) i reparació artroscòpica total. Es van avaluar els resultats funcionals mitjançant la puntuació de la part posterior del peu i l'escala de dolor analògic visual (VAS) de la American Orthopaedic Foot & Ankle Society (AOFAS) pre i postoperatori. Es van registrar l'amplitud de moviment i les complicacions i analitzar i comparar els resultats d'ambdues tècniques.

El segon estudi clínic és una sèrie de casos de 18 pacients amb CAI sotmesos a una reparació artroscòpica total. L'avaluació es va fer mitjançant les proves AOFAS, VAS, calaix anterior i inclinació de l'astràgal. Es van registrar l'amplitud de moviment i les complicacions.

Resultats: En el primer estudi anatòmic, tots els exemplars examinats van identificar les fibres que connecten l'ATFLif i la CFL. El transductor de desplaçament va indicar un allargament del CFL en totes les mesures, amb un allargament mitjà de 0,59 mm (SD ± 0,34). En la investigació anatòmica posterior utilitzant tècniques avançades d'exploració òssia, es va establir de manera concloent que les àrees d'inserció ATFLif, CFL i del lligament talofibular posterior (PTFL) són contínues al llarg de l'aspecte medial del peroné. Aquesta anàlisi va obtenir una àrea d'inserció unificada amb una mesura mitjana de 4,8 cm² (± 0,7 cm²). En particular, en 9 dels 11 peus avaluats, l'àrea d'inserció del ATFL a l'astràgal constava de dues parts diferents, mentre que es va observar una inserció contínua als 2 peus restants. A més, la inserció del CFL al calcani es va caracteritzar com una àrea d'inserció singular en tots els casos revisats.

En el primer estudi clínic, el grup AB estava format per 20 pacients amb una edat mitjana de 30,2 (18-42) anys i un seguiment mitjà de 19,6 (12-28) mesos. El grup de reparació integral artroscòpica estava format per 19 pacients amb una edat mitjana de 30,9 (rang, 18-46) anys i un seguiment mitjà de 20,7 (rang, 13-32) mesos. En ambdós grups, les puntuacions AOFAS i VAS van millorar significativament en comparació amb els valors preoperatoris (P <0,001), sense cap diferència (P>0,001) entre grups.

Al grup AB, la puntuació mitjana AOFAS va millorar de 67 (rang, 44-87) a 92 (rang, 76-100), i la puntuació mitjana de l'EVA de 6,4 (rang, 3-10) a 1,2 (rang, 0-10). 3). En el grup AI, la puntuació mitjana AOFAS va canviar de 60 (rang, 32-87) a 93 (rang, 76100) i la puntuació mitjana de l'EVA de 6,1 (rang, 4-10) a 0,8 (rang, 0-10). 3). Es van registrar vuit complicacions (40%) en el seguiment final del grup AB. En el grup de reparació artroscòpica total, es va observar una complicació (5, 3%) ($p < 0,05$). El segon estudi clínic va analitzar 18 pacients amb un període mitjà de seguiment de 12 mesos. Hi va haver una millora en l'AOFAS ($p <0,001$), amb la millora mitjana de 69,6 punts a 98,1, desviació estàndard (DE) = 11,09, i en la puntuació mitjana de l'EVA ($p <0,001$), de 5,0 a 0,5 punts (DE). = 0,78). Tots els turmells eren estables, tal com es van avaluar les proves d'inclinació del calaix anterior i de l'astràgal. L'única complicació trobada va ser la neurapràxia del nervi fibular superficial en un pacient (5%). Tots els pacients van classificar el tractament com a bo o excel·lent i van tornar a les activitats esportives sense limitacions.

Conclusions: Les fibres de connexió entre l'ATFLif i la CFL són prou fortes per transferir la tensió d'una estructura a una altra. L'ATFLif, el CFL i el PTFL comparteixen una àrea d'inserció contínua a la part medial del peroné. El tractament de la CAI amb reparació anatòmica artroscòpica de l'ATFL produeix excel·lents resultats clínics i funcionals amb una baixa taxa de complicacions.

8. Introduction

This PhD thesis focuses on research related to the lateral ligaments of the ankle. It is presented as a compendium of publications from studies conducted in collaboration with professors from the University of Barcelona and orthopedic surgeons over the last four years (2021-2024). Two publications from this project were showcased at the 50° and 55° Brazilian Congress of Orthopedic and Traumatology in 2020 and 2023, organized by the official Brazilian Orthopedic Society, and received two awards for the best anatomical free paper.

8.1 Background

Ankle sprains are common injuries involving the lateral collateral ligament (LCL) and represent one of the most common causes of orthopedic consultations. They account for around 25% of all musculoskeletal system injuries.(1) In the United Kingdom emergency department, approximately 5000 ankle sprains occur daily. In the United States, approximately 2 million acute ankle sprains occur annually.(2) They affect general and young patients who regularly engage in physical activities. Approximately 40% of all traumatic ankle injuries and nearly half of all ankle sprains occur during athletic activity, with basketball (41.1%), American football (9.3%), and soccer (7.9%) having the highest incidence. (3)

Regarding elite athletes, acute ankle sprains are particularly high among elite basketball players. The incidence rate of acute ankle sprains among National Basketball Association players is approximately 3.2 to 3.5/per 1000 player games. (4) Similarly, ankle sprains were the most common specific diagnosis, representing 19.8% of all injuries among professional volleyball players. (4, 5) Furthermore, foot and ankle injuries account for 20% of all English Premier League club football injuries, with the LCL being the most affected in 31%. (6) In addition to the negative impact on patient's quality of life, this high rate of lateral ligament injuries also generates a significant economic impact, which includes the direct medical cost of the injury but also the indirect medical cost, such as loss of productivity (sports time lost, missing school due to disability and work absence). (6)

Beyond the impact on the individual's quality of life, acute ankle sprains with LCL injuries can develop a high recurrence rate and chronic ankle instability (CAI), which has long-term consequences that may impact patient outcomes.(3, 7) After a new ankle sprain, there is an increased risk of associated lesions such as an ankle fracture, cartilage injury of the talus, or syndesmotic injuries.(7, 8) Syndesmotic or “high ankle” sprains are reported in one of every five athletes undergoing magnetic resonance evaluation after an acute ankle sprain and correlate with prolonged pain, dysfunction, and return to sports. (9)

8.2 Ankle Anatomy

Anatomical knowledge of the lateral ankle ligaments is fundamental for improving diagnostic methods and developing effective surgical treatments for CAI. A precise understanding of the LCL enables surgeons to perform accurate repairs and reconstructions, leading to better clinical outcomes. Anatomical research significantly impacts the advancement of orthopedic surgery by improving the understanding of complex structures and biomechanics. In-depth anatomical knowledge allows surgeons to navigate this intricate anatomy precisely, reducing the risk of complications and enhancing the overall success of surgical interventions. Additionally, anatomical research is helpful in the development of innovative procedures and technologies, ultimately improving the quality of treatments and patient satisfaction. (10-12)

Cadaveric dissection is the most effective method for performing anatomical research. The use of human cadavers makes possible the examination of anatomical structures, spatial relationships, and variations in real-life scenarios. This real exposure boosts the advancement of medical research, making it a genuine platform to explore disease processes, surgical techniques, and the development of innovative medical technologies. This is especially important for the ankle lateral ligaments since their complex anatomy has yet to be fully comprehended. (13, 14) For this reason, two of this thesis's studies performed anatomical studies of the lateral ligamentous complex in cadaveric specimens.

8.2.1 Ankle Joint

The ankle joint comprises three bones: the tibia, fibula, and talus. Three ligament complexes connect and stabilize these bones: the LCL, the medial collateral ligaments (MCL), and the syndesmotic ligaments. (Figure 1) The talocrural joint, also known as the tibiotalar joint, is a critical articulation involving the dome of the talus, tibial plafond, medial malleolus, and lateral malleolus. The biomechanics of the talocrural joint are crucial for the function and stability of the ankle complex. This hinge joint facilitates plantarflexion and dorsiflexion movements. During weight-bearing activities like walking or running, the talocrural joint undergoes complex motions involving both rolling and sliding mechanisms. This joint is a component of the ankle joint complex, encompassing the subtalar and transverse tarsal joints and contributing to the foot's multiaxial function. (15-18)

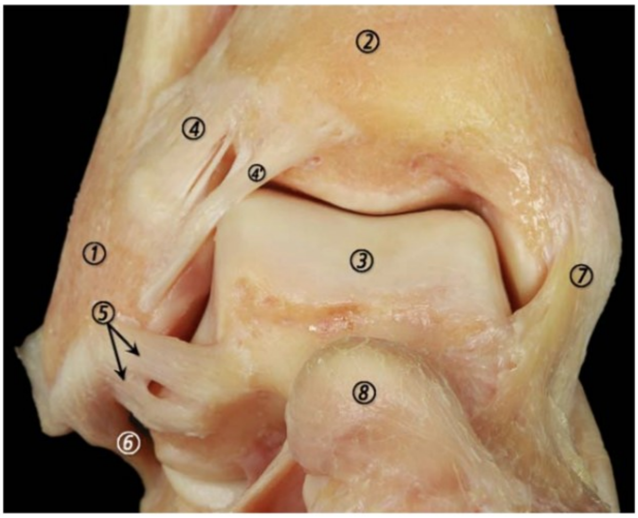

Fig 1. Anatomic view of the anterior ligaments of the ankle. (1) lateral malleolus; (2) tibia (3) talus (4) anterior tibiofibular ligament (4) distal fascicle of the anterior tibiofibular ligament (5) anterior talofibular ligament (6) calcaneofibular ligament (7) superficial and deep layers of the medial collateral ligament (8) head of the talus. By Golano et al. (19)

The surrounding ligament complexes influence the stability of the ankle joint. Changes in the biomechanics of the talocrural joint, such as limited ankle dorsiflexion, have been linked to a higher risk of injuries in other joints, such as the knee. Moreover, the talocrural joint collaborates with the subtalar joint to generate coordinated movements during activities like walking and running. The subtalar joint contributes to inversion and eversion movements, working with the talocrural joint to ensure proper foot and ankle function. The intricate interplay between these joints is essential for preserving balance, stability, and efficient gait patterns. (15-17)

8.2.1 Lateral Ligaments of the Ankle

The LCL, which includes the anterior talofibular ligament (ATFL), the calcaneofibular ligament (CFL), and the posterior talofibular ligament (PTFL), is crucial for lateral stability to the ankle joint and is commonly involved in inversion injuries. (20) The LCL complex maintains ankle stability by limiting talar anterior translation and internal rotation. The LCL is particularly affected after an ankle sprain, with approximately 80% of injuries involving the ATFL and the remaining cases resulting from combined damage to the ATFL and CFL. The PTFL is the strongest lateral ligament and is rarely affected. (20, 21)

The Anterior Talofibular Ligament

The ATFL is the primary restraint for anterior talar translation and is often injured in lateral ankle sprains. It typically comprises two fascicles (superior and inferior) separated by an interval that allows penetration of the vascular branches from the perforating peroneal artery and its anastomosis with the lateral malleolar artery. The ATFL's superior fascicle (ATFLsup) is an intraarticular structure. It has a fibular insertion located just below the distal insertion of the antero-inferior tibiofibular ligament (ATIFL) at the anterior aspect of the fibula. It runs anteriorly and horizontally to be inserted on the talar neck, close to the talar dome's articular surface. (18,22,23) The ATFLsup is observed to become lax in ankle dorsal flexion and taut in plantar flexion, as shown in dynamic observations. The ATFL's inferior fascicle (ATFLinf) is an extraarticular isometric structure that shares a common fibular origin at the inferior tip of the fibula with CFL. From the fibular origin, the ATFLinf runs anteriorly, parallel to the ATFLsup, to attach to the talar neck just below the talar insertion of ATFLsup. (Figure 2)

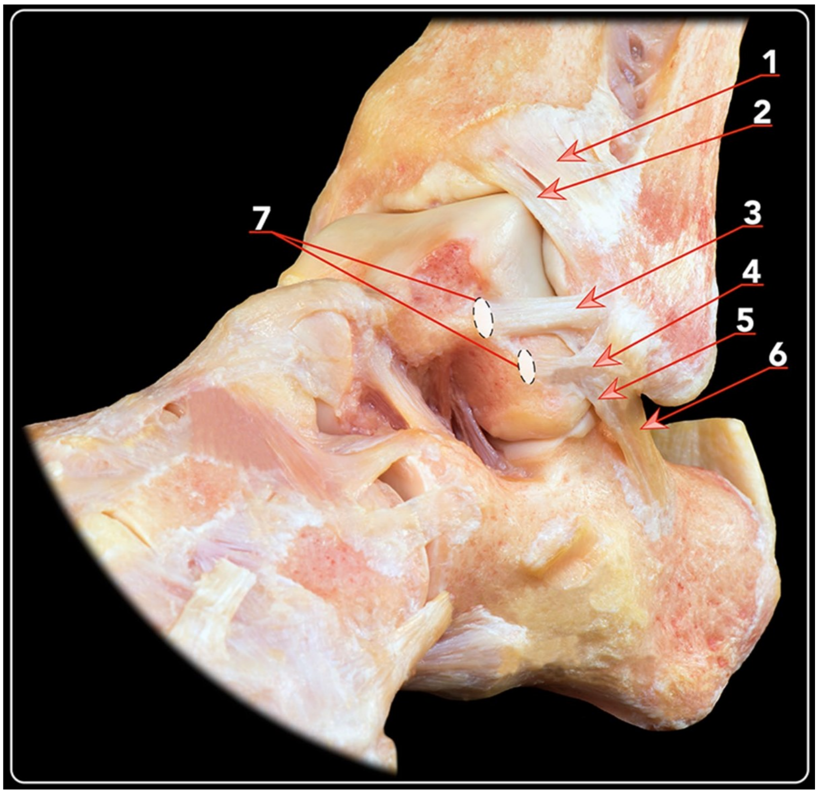

Fig 2: Lateral view of an osteoarticular dissection demonstrating the anatomy of the lateral ligaments of the ankle. (1) Anterior tibiofibular ligament. (2) Distal fascicle of the anterior tibiofibular ligament. (3) ATFL superior fascicle. (4) ATFL inferior fascicle. (5) Arciform fibers (6) CFL. (7) Note the different talar insertion points of ATFL fascicles. By Vega et al.(25)

Furthermore, the inferior border of the ATFLinf and the anterior border of the CFL are connected through arciform fibers and were observed as isometric structures. Considering these anatomical correlations, the ATFLinf, CFL, and their connections are described as a single functional anatomical structure named the lateral fibulotalocalcaneal ligament complex (LFTCL). (Figure 3) (24, 25) At this point, whether the connecting fibers are robust enough to transmit tension from ATFLinf to CFL is unknown. Understanding the mechanical relationships between the components of the LCL is important for the pathogenesis, diagnosis, and treatment of CAI. When surgical treatment is needed, the LFTCL complex, as a functional unit with connections between its components, would suggest that a single act on one of its components will affect the other. One study of this thesis evaluated the ability of the connecting fibers between ATFLinf and CFL to transmit tension between them through a dynamic measurement analysis.

Fig 3. Morphology of the lateral ankle ligaments in plantarflexion (**a**) and dorsal flexion (**b**) by Vega et al. (25) Note how the structures forming the LFTCL are isometric throughout the range of motion while the ATFL sup does not. (1a) Taut ATFL superior fascicle (1b) Lax ATFL superior fascicle (2) ATFL inferior fascicle (3) Connecting fibers between the ATFLinf and CFL, forming the LFTCL complex (4) CFL

<u>The Calcaneofibular Ligament</u>

The CFL has a distinct function because it is the only ligament connecting the talocrural and subtalar joints. It is a cordlike or flat and fanning band extraarticular structure, and most of the ligament is covered by the peroneal tendons sheath. This ligament has a common fibular origin with the ATFLinf. It runs in a posterior-inferior direction under the peroneal tendons sheath to insert into the small tubercle at the posterior aspect of the lateral calcaneus surface. (Figure 4) (26-28)The CFL is a critical stabilizer of the lateral ankle, contributing significantly to ankle stability by preventing excessive inversion and providing resistance to the talar tilt. The ligament's length varies between
18.5 and 35.8 mm. Its width ranges from 4.6 to 7.6 mm. The insertion of the CFL on the calcaneus is approximately 12.1 to 13 mm from the subtalar joint or 13.2 to 27.1 mm from the peroneal tubercle on the lateral wall of the calcaneus. The CFL is often injured with the ATFL during ankle sprains, leading to significant lateral ankle instability.

The ligament's morphology can vary, with some specimens presenting as a single bundle while others exhibit Y-shaped or V-shaped double bundles. (24, 26, 27, 29)

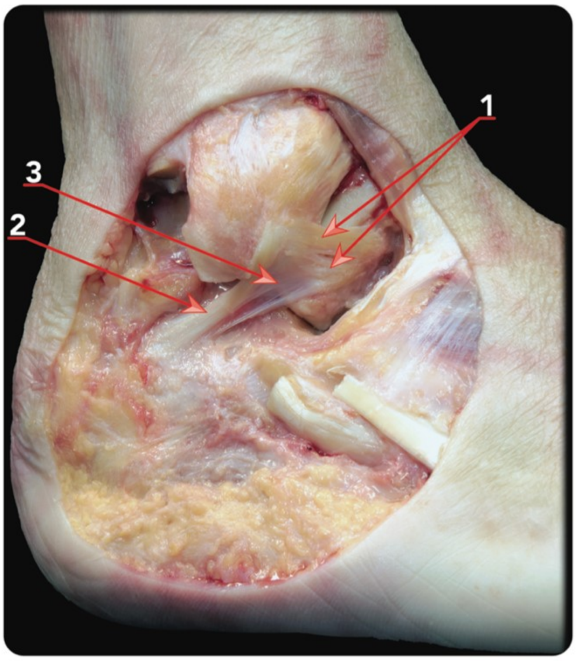

Fig. 4: Anatomic dissection of lateral ankle ligaments by Dalmau et al. (23)
(1) ATFL, superior and inferior fascicles (2) CFL (3) Connecting fibers between the ATFLinf and CFL.

The Posterior Talofibular Ligament

The PTFL is recognized as a crucial component of the LCL complex of the ankle joint. This ligament demonstrates different states of tension during ankle movements, being relaxed during plantar flexion and tensioned during dorsiflexion. Anatomically, the PTFL is a multifascicular ligament originating from the lateral malleolus's malleolar fossa on the medial surface. It runs nearly horizontally to insert in the posterolateral aspect of the talus, with some fibers potentially extending to the lateral talar process. The PTFL significantly contributes to ankle stability and is rarely affected in an ankle sprain. (18, 30)

The PTFL, ATFL, and CFL create the ankle's LCL complex. The literature contains many anatomical studies about these structures. Although earlier literature assessed the anatomy of the ankle's LCL, many aspects remain unknown. Most anatomical studies of the LCL focused on analyzing its length, width, and bone landmarks. Additionally, they were carried out in a two-dimensional view with a digital caliper or goniometer.(26-28) A recent anatomical study demonstrated that this anatomical region is far more complex. They showed that the LCL complex is connected through medial fibers between ATFL and PTFL, ATFL and CFL, and CFL and PTFL, raising new perspectives on diagnosing and treating CAI.(Figure 5) (24) Therefore, further investigation of these new concepts is needed using a 3D assessment. Another study of this thesis aimed to assess the anatomical characteristics of the LCL and their relationships through a three-dimensional view.

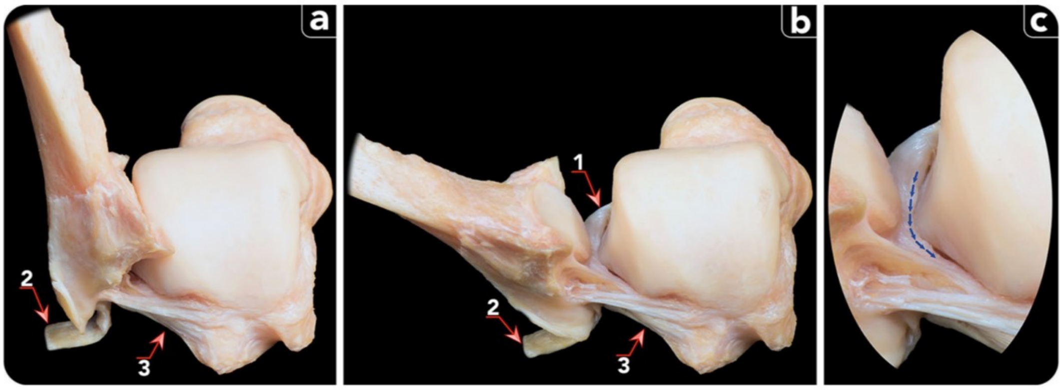

Fig 5. (a) Posterior view of talus and fibula in its anatomical position by Dalmau et al.(24). (b) and (c) the fibula is displaced laterally to show the connections between ATFLsup and PTFL (1) ATFLsup (2) CFL (3) PTFL

8.2.2 Ankle Syndesmosis

The ankle syndesmosis is a fibrous joint formed by the distal epiphysis of the tibia and fibula. It’s a joint stabilized by four ligaments that plays a significant role in maintaining the congruency of the tibiotalar joint interface under physiologic axial loading. The tibia bears the most weight, while the fibula supports stability and balance. The syndesmosis ensures these bones move in unity, distributing loads and forces appropriately across the ankle joint. The syndesmosis ligaments ensure that the tibia and fibula remain together, especially during ankle dorsiflexion and external rotation (31,32). The ligamentous structures that compose the ankle syndesmosis include the ATIFL, posterior tibiofibular ligament (PTIFL), the interosseous tibiofibular membrane, and the interosseous ligament.

Anterior Tibiofibular Ligament

The ATIFL is the most affected in syndesmotic injuries, often resulting from external rotation or dorsiflexion forces applied to the ankle. The ATIFL extends obliquely from the tibial anterior tubercle to the anterior part of the fibular malleolus, running from proximal-medial to distal-lateral and crossing the anterolateral corner of the talus. (33, 34) The ATIFL has a multifascicular aspect caused by fatty tissue interposed between the multiple collagen bundles. Viewed in a coronal plane, it comprises three bundles, separated by 2-mm-wide gaps that converge slightly in the latero-distal direction and consequently give the ATIFL a trapezoidal shape. The upper part of the ATIFL is the shortest one. It originates just above the anterior tubercle of the tibia and is attached just above the anterior tubercle of the fibula. This ligament has a constant distal fascicle, is intra-articular, and is covered by synovial tissue. It crosses the proximo-lateral margin of the ankle and is in contact with the anterolateral part of the talar dome during plantarflexion; that contact is reduced in dorsiflexion. The ATIFL is the weakest syndesmotic ligament and is the first to yield to forces that create an external rotation of the fibula around its longitudinal axis. (Figure 6) (31, 34, 35)

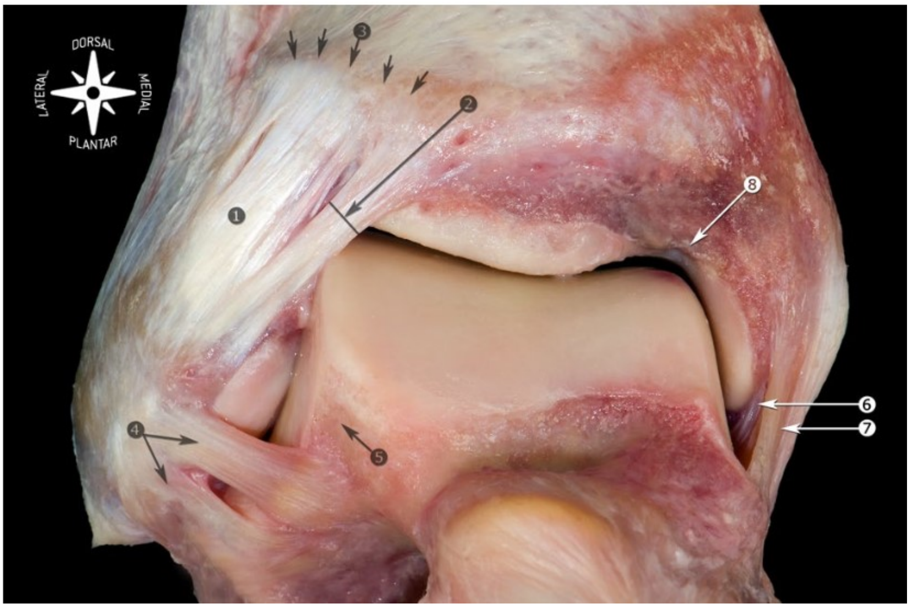

Fig 6. Anatomic view of the anterior ligaments of the ankle. By Golano et al.(18) (1) Anterior tibiofibular ligament (2) distal fascicle of the anterior tibiofibular ligament (3) tibia (anterior tubercle indicated with arrows) (4) anterior talofibular ligament (5) beveled triangular region of the talus; 6 deep layer of the medial collateral ligament (7) superficial layer of the medial collateral ligament (8) notch of Harty

Posterior Tibiofibular Ligament

The PTIFL is a strong ligament that extends from the posterior tibial malleolus to the posterior tubercle of the fibula and runs from proximal-medial to distal-lateral. It is less frequently injured than the ATIFL but significantly stabilizes the ankle syndesmosis, particularly against external rotation forces. It is multifascicular, with a superficial and a deep fascicle (also called transverse ligament in the arthroscopic literature (18). Some PTIFL superficial fibers originating from the fibular insertion sometimes appear continuous with the deep fascicle (33), a ligament that extends intra-articularly, deepening the articular surface of the tibia. This structure is covered by fibrocartilage, forms a true labrum, and can be identified separately from the superficial PTIFL (36)

Intermalleolar ligament

The intermalleolar ligament is situated between the fibular insertions of the PTIFL. Literature describes it as an intra-articular extrasynovial structure that strengthens the posterior ankle joint capsule. It can be observed during anterior arthroscopy when distraction is applied (31).

Interosseous Membrane and Ligament

The interosseous membrane extends between the tibia and fibula. It thickens at its lowermost end to form a pyramidal-shaped structure known as the interosseous ligament. Most of its fibers run in a latero-distal and anterior direction from the tibia to the fibula, although some fibers on the anterior aspect run reversely. The most distal fibers attach to the tibia at the anterior tubercle level and descend straight to the fibula, where they attach just above the level of the talocrural joint. The most proximal fibers attach to the tibia at the apex of the incisura tibialis. The area underneath the interosseous ligament is occupied by the synovial recess of the tibiofibular syndesmosis, where the synovial fringe can also be found. (33, 34)

8.2.3 Medial Ligaments of the Ankle

The MCL, known as the deltoid ligament, is a robust and broad ligament that stabilizes the medial aspect of the ankle joint complex. Although there are variations in anatomical descriptions, the deltoid ligament is generally considered to have superficial and deep components formed by multiple thickenings in a common capsular band. It is a multifascicular ligament originating from the medial malleolus and inserting into the talus, calcaneus, and navicular bone. (1) A traditional anatomical study observed the MCL with four superficial and two deep components. It described the superficial layer as formed by the tibionavicular, tibiospring, tibiocalcaneal, and superficial posterior tibiotalar ligaments, while the deep layer was formed by the anterior and posterior tibiotalar ligaments. (37) The most recent anatomical study described the MCL as divided into superficial and deep layers with four ligamentous bands. The superficial layer contains the longest ligament fibers and comprises the talonavicular, tibiospring, and tibiocalcaneal fascicles. (Figure 7) The deep layer consists only of the tibiotalar fascicle, which has the shortest fibers and is entirely intra-articular. The tibiotalar fascicle can be divided into an anterior (or pre-collicular), intermediate (or collicular), and posterior (or post-collicular) part based on its origin on the anterior colliculus of the medial malleolus. (38) The MCL contributes significantly to medial and rotational ankle joint stability. Depending on the foot's position, different parts of the deltoid ligament can stabilize against varying movements. The superficial ligaments resist valgus and external rotation of the talus in the tibiotalar joint. Although the superficial layer is separated from the deep layer by adipose tissue, the posterior and middle portions of the ligaments have a strong attachment to the posterior tibial tendon sheath. The deltoid's deep layer stabilizes the ankle joint against plantarflexion by preventing lateral displacement of the talus and restraining external rotation. (39, 40)

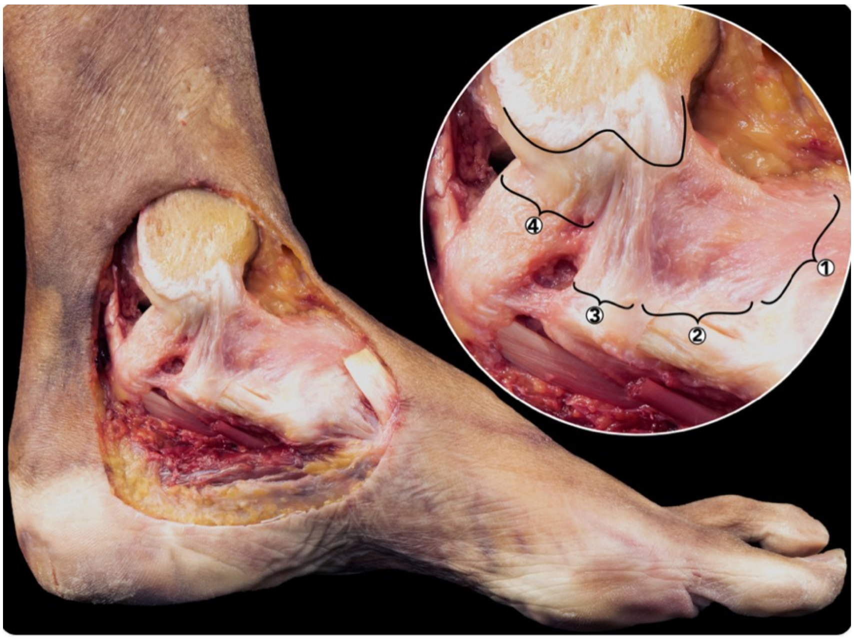

Fig 7. Dissection showing the deltoid ligament. The anterior and posterior colliculus have been outlined by Dalmau et al.(38) (1) Tibionavicular fascicle. (2) Tibiospring fascicle. (3) Tibiocalcaneal fascicle. (4) Posterior part of the tibiotalar fascicle (deep deltoid).

As a crucial static stabilizer of the medial ankle joint, an injury to the deltoid complex can result in the displacement of the talus within the ankle mortise. Within the deltoid complex, the superficial layers resist external rotation and valgus stress on the ankle and hindfoot. In contrast, the deep layer counteracts ankle eversion and lateral migration of the talus. This is significant during the gait cycle, as any injury to the deltoid complex impacts not only the medial longitudinal arch but also tibial rotation and foot inversion. Pathological translation and rotation of the talus within the mortise can lead to modified ankle biomechanics and symptoms of instability. Medial ankle sprains have been shown to develop osteoarthritis at a rate even greater than lateral-sided injuries, thus warranting careful evaluation. (41, 42)

8.3 Chronic Ankle Instability

Approximately 20 % of acute ligament lesions in the lateral compartment of the ankle advance to CAI, which is resistant to medical treatment and causes repeated sprains. (43) CAI encompasses a spectrum of clinical conditions involving minor or significant lateral ankle instability in athletes and lower-demand patients. Significant or mechanical instability, or actual anatomical instability, occurs when the ankle range of motion exceeds the physiological limit of joint motion due to laxity caused by incompetent stabilizing structures such as lax or ruptured ligaments. This laxity can be clinically demonstrated in specific clinical maneuvers. (7, 43) Minor instability, also referred to as functional instability, is defined as a subjective feeling of the ankle or foot giving way without objectively demonstrable clinical or radiological deviation of ankle joint motion beyond the physiological range of motion of the talus. In contrast to mechanical instability, altered neuromuscular recruitment patterns, such as abnormal peroneal muscle spindle activities and mechanoreceptor activities, increased peroneal response time, and impaired reflex response to inversion/supination, have been reported to contribute to functional instability of the ankle. (44, 45) The new anatomical concepts discussed in this thesis showed that functional instability seems to be an isolated injury of the ATFLsup, which can lead to subtle instability and chronic anterolateral ankle pain, known as microinstability. (23, 46, 47)

8.4 Clinical Exam

When assessing a patient with CAI who has had a new ankle sprain episode, a thorough clinical examination is essential to gather important information about the condition's extent and guide appropriate treatment strategies. Concomitant lesions must also be evaluated. The clinical exam typically involves a comprehensive review of the patient's history, symptoms, functional limitations, and physical findings related to the ankle joint. (48, 49)

The initial symptoms of acute lateral ankle ligament sprains commonly include pain, swelling, bruising, and limited weight bearing. While a physical examination during the acute phase may cause discomfort, assessing and ruling out potential fractures in the ankle, the base of the fifth metatarsal, or the talar lateral process, is crucial. Limited range of motion and tenderness upon palpation over the affected ligaments are typical findings. Performing a follow-up examination after the initial phase of pain, swelling, and protective responses have diminished can significantly enhance the sensitivity of the evaluation, as a global consensus conference recommended, emphasizing the importance of delayed physical examination for accurately diagnosing ankle instability. (4,50)

In some cases of ankle sprain, there is an associated acute syndesmotic injury. Patients with syndesmotic injuries often experience ankle pain, swelling, reduced dorsiflexion, bruising, and difficulty on weight bearing. Tenderness is typically localized in the distal tibiofibular syndesmosis area. However, about 40% of patients may also report pain over the ATFL. Occasionally, medial pain during dorsiflexion or push-off while walking may also accompany these injuries. This complex presentation underscores the need for a comprehensive evaluation to effectively diagnose and manage syndesmotic injuries. (35,51,52)

Nonetheless, symptoms of CAI may persist for more than six months. Patients commonly experience sensations of the ankle "giving way," frequent sprains, persistent ankle pain, swelling, episodes of locking, mechanical symptoms, and restricted range of motion. (4,43,49) CAI can manifest in different scenarios, such as a single sprain event with ongoing pain, multiple sprains combined with pain-free periods, or repeated sprains accompanied by discomfort between episodes. In cases of the latter scenario, patients often notice that pain and sensations of instability intensify after each sprain, prompting them to seek medical attention for evaluation and management (43,53)

For the physical exam, examining both ankles for comparison is essential. Significant variations in joint laxity exist among individuals, depending on genetics, age, and gender. Since this affects both limbs equally, comparing the contralateral side provides a better sense of the underlying instability. Specific tests for lateral ankle instability include the Anterior Drawer Test and the Talar Tilt Test (Figure 8). The Anterior Drawer Test is a fundamental examination technique used to assess ankle stability; however, factors such as patient positioning and ligament laxity can influence its accuracy. To ensure reliable results, positioning the patient correctly is crucial, allowing the gastrocnemius complex to relax. Clinicians can detect instability by applying an anterior force on the hindfoot and observing any anterior translation. Incorporating an internal rotation force can further enhance the test's specificity by minimizing the effects of the deltoid ligament on the interpretation of the results.

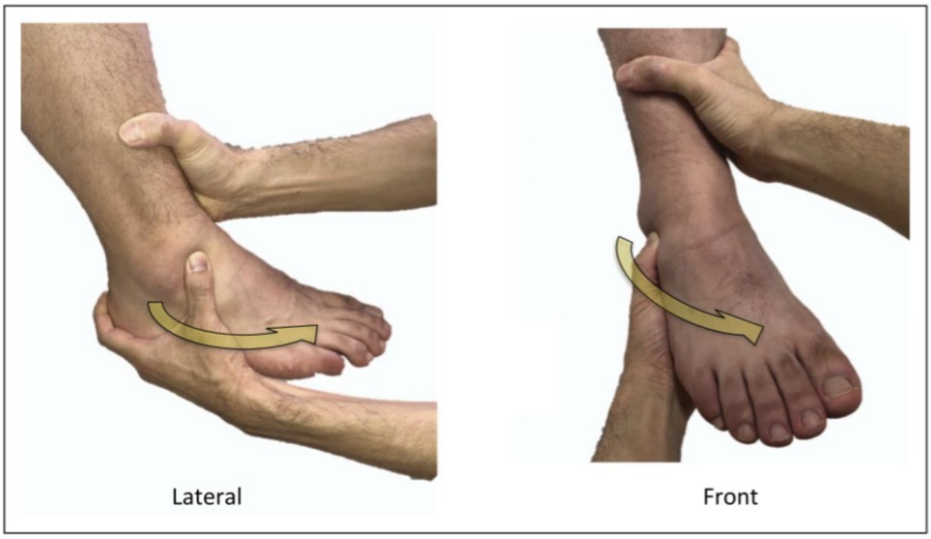

Fig 8. The anterolateral drawer test is performed with the hindfoot held with the thumb overlying the lateral joint line and the ankle plantarflexed 10 to 15 while the other hand stabilizes the tibia. While pulling the foot forward, the foot can rotate internally, and the palpating thumb assesses any progressive step-off between the anterior fibula and the lateral talus. By Chang et al. (57)

In contrast, the Anterior Drawer Test assesses not only the anterior translation of the talus but also involves a rotational aspect affected by the integrity of the deltoid ligament. This rotational movement and direct translation should be considered for a thorough evaluation. (7,58) While the Talar Tilt Test is useful for evaluating lateral ankle stability, it may face difficulties isolating the specific ligaments due to possible contributions from the subtalar joint. By carefully adjusting foot positioning and analyzing any tilt or angulation differences relative to the healthy side, clinicians can still obtain insights into the ligaments' integrity despite potential confounding factors. (55, 59)

Functional tests for lateral ankle instability are used to assess strength, balance, proprioception, and functional performance. Testing for proprioception and balance can help identify deficits that may contribute to recurrent ankle sprains and instability. Strength and stability of the ankle musculature, particularly the peroneal muscles, are assessed to assess the ankle's ability to support weight and resist inversion stress.(60, 61) These tests include the Single Leg Balance Test, Star Excursion Balance Test, hop tests, agility assessments, ankle instability questionnaires, and dynamic balance evaluations such as the Y-Balance Test (Figures 9 and 10). An isokinetic dynamometer is also a helpful tool. By evaluating the patient's ability to maintain balance, dynamic balance, power, and agility, these tests aid in tailoring rehabilitation programs and tracking improvements in ankle stability and function over time.(61-63)

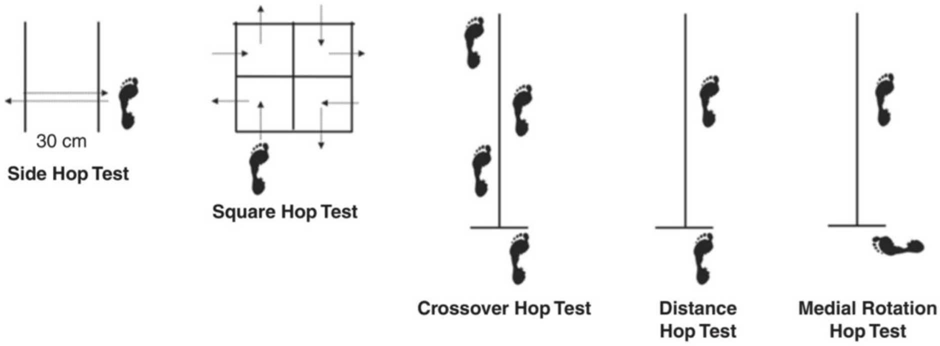

Fig 9. Hop test battery including side hop, square hop, crossover, linear hop for distance, and medial rotation hop for distance test. By D'Hooghe et al.(53)

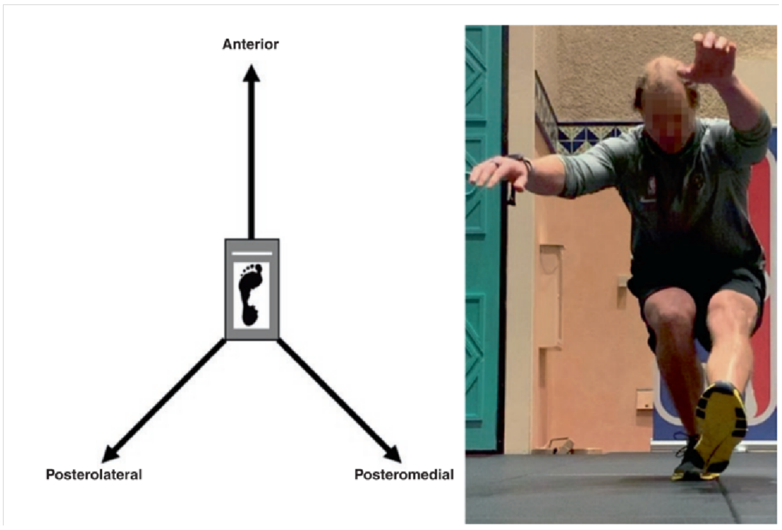

Fig.10: Y Balance Test with anterior reach demonstration. By D'Hooghe et al. (53)

In the chronic setting, a comprehensive clinical examination is crucial to explore into the multifaceted aspects of ankle instability. Beyond stability assessments, the focus broadens to encompass an in-depth evaluation of the range of motion in the ankle and subtalar joints. Ankle instability has been associated with decreased plantar flexion/dorsiflexion range of motion. The lunge test is the most applicable and reliable method for assessing ankle joint dorsiflexion range of motion. It is vital to pinpoint and scrutinize areas of chronic pain, meticulously correlating them with potential sources such as lateral and medial ankle ligaments, peroneal tendons, or joint line pain to uncover the underlying contributors to instability. (64-66)

A thorough assessment must also be conducted to determine the factors that could exacerbate instability. This includes evaluating hindfoot varus and arch height to better understand the foot's biomechanics. These factors play pivotal roles in shaping the mechanical environment of the ankle and influencing its overall stability. (67-69) Furthermore, scrutiny of potential anterior or posterior impingement symptoms is essential, as these could further complicate the clinical picture and impact the patient's functional ability. (70)

Clinical examination of syndesmotic injuries presents a challenge due to the lack of a definitive gold-standard diagnostic maneuver. Specific tests can be difficult to interpret during the acute phase and may lack predictive value; however, they play an essential role in raising suspicion and guiding further imaging assessments when combined with a supportive clinical history. (71, 72) Tests utilized in clinical evaluation include tenderness on palpation over the anterior or posterior syndesmosis, the squeeze test for tibiofibular pain, the Cotton test for talus translation, the fibular translation test for ligamentous injury, syndesmosis tenderness length measurement for injury severity, the cross-legged test for eliciting syndesmotic pain, external rotation stress test for balanced sensitivity/specificity in instability assessment, single leg jump test for pain response with or without stabilization, and dorsiflexion lunge to evaluate range of motion and pain. When used together, these tests assist in diagnosing and managing syndesmotic injuries effectively. (35, 53, 71, 72)

8.5 Risk Factors

CAI is characterized by recurrent sprains, persistent pain and swelling, insecurity about playing sports, and a drop in sporting performance. Up to 40% of individuals develop CAI following an acute ankle sprain, which is higher in patients with specific risk factors. (7, 73)

8.5.1 Intrinsic Risk Factors

The intrinsic factors include generalized hyperlaxity, limited dorsiflexion range of motion, reduced proprioception (preseason deficiencies in postural control/balance), high medial plantar pressures during running, and hindfoot varus deformity. Additional factors contributing to increased risk are reduced strength, coordination, cardiorespiratory endurance, limited overall ankle joint range of motion, and decreased peroneal reaction time. (64, 74, 75)

An important factor related to CAI is cavovarus foot deformity. This deformity alters foot mechanics, putting additional strain on the lateral foot column and elevating the risk of ankle instability. Understanding the connection between the cavovarus foot and CAI is essential, as addressing the underlying cavovarus alignment is crucial for achieving successful treatment outcomes and long-term stability. Failure to correct the hindfoot varus is a significant cause of recurrence in CAI surgical treatment. For subtle deformities, the initial strategy can include a conservative approach with orthotic interventions and strengthening exercises to enhance ankle balance and proprioception. For severe cavus foot deformities, a combined surgical intervention involving calcaneus or metatarsal osteotomies and lateral ligament repair is necessary to ensure favorable long-term outcomes and reduce the risk of ankle instability recurrence. (67, 68)

8.5.2 Extrinsic Risk Factors

Extrinsic factors related to lateral ankle sprains, such as the type of sport practiced, play a significant role in the occurrence of these injuries. Research has indicated that the highest incidence of lateral ankle sprains is observed in sports like basketball, indoor volleyball, field sports, and climbing, with the incidence varying based on the level of participation. For instance, landing after a jump is a crucial risk factor for ankle sprains in volleyball. Similarly, playing soccer on natural grass and assuming the role of a defender have been associated with an increased risk of ankle sprains. Furthermore, the choice of footwear can also influence the risk of ankle sprains, with high heels being identified as an essential related risk factor. (48, 73-75)

8.6 Associated Lesions

CAI is frequently associated with various intra-articular pathologies and complications, such as peroneal tendinopathy, osteochondral lesions, anterior impingement, rotational instability, and osteoarthrosis. Pathological abnormality of the peroneal tendons is an under-appreciated source of lateral hindfoot pain and dysfunction related to CAI. The tendons are the primary evertors of the foot and function as lateral ankle stabilizers, with pathology falling into categories such as tendinitis, tenosynovitis, tendon subluxation, dislocation, splits, and tears. (74, 75) Approximately 30% of patients with CAI have osteochondral lesions predominantly located on the talus, especially the medial talar dome. Several risk factors influence the development of osteochondral lesions of the talus in the context of CAI, such as male sex, older age, and a post-injury duration of five years or longer. Furthermore, both ATFL and CFL injuries enhance the chance of developing these associated lesions. (75, 76)

8.7 Natural Progression

The natural progression of CAI begins with the development of rotational instability due to injury to the deltoid ligament complex. This condition is marked by altered biomechanics, including increased internal rotation and inversion of the talus. As lateral ankle instability and multidirectional instability persist, degenerative consequences may arise in the ankle joint. Degenerative changes can involve osteoarthritis, cartilage damage, bone spurs, and joint degeneration. These changes can result in pain, stiffness, swelling, and a reduced range of motion in the ankle joint, impacting overall function and quality of life. Early intervention, accurate diagnosis, and customized treatment strategies are crucial for addressing these issues and preventing long-term complications associated with CAI. (41, 50, 77)

The high frequency, economic, and clinical impact of ankle sprains with LCL lesions emphasizes the need for effective prevention strategies and optimal treatment approaches. (6, 45) Studying the LCL's biomechanics, pathophysiology, and anatomy is imperative. Understanding the mechanisms of injury, risk factors, and associated complications can help develop targeted injury prevention programs and interventions to reduce the burden of lateral ankle ligament injuries in athletic and non-athletic populations. (3, 74)

8.8 Complementary Exams

Complementary exams are crucial in assessing lateral ankle instability. They provide additional information that may not be apparent through clinical evaluation alone. These exams help confirm the diagnosis, determine the severity of the injury, evaluate the presence of associated lesions, and guide appropriate treatment strategies. The most used imaging exams are radiography, ultrasonography, magnetic resonance imaging, and computed tomography. (8, 54, 78, 79)

8.8.1 Radiography

Radiography is a straightforward exam that should be requested after an ankle sprain when there is a clinical suspicion of a fracture, according to the Ottawa rules. (3) Its primary role is to assess the presence of related injuries, particularly ankle fractures, fractures of the base of the fifth metatarsal bone, and issues with the lateral process of the talus. It can also identify ankle alignment and morphological changes that may contribute to instability. (8)

Another option discussed in the literature is performing stress radiography to assess the degree of instability in the ankle joint. (80) A significant limitation of using stress radiography to evaluate lateral ankle instability is that it may only capture certain aspects of this instability, particularly in multifactorial cases or those that involve structures beyond the lateral ligaments. Moreover, the force applied to induce stress is subjective and may not accurately reflect the necessary pressure to cause instability. These limitations oversimplify the complexity of instability and its associated pathologies. For these reasons, stress radiography is no longer recommended. (54)

8.8.2 Ultrasonography

Ultrasonography is a valuable diagnostic tool for evaluating CAI, offering a range of benefits that enhance the assessment process. Its real-time imaging capacity allows for dynamic evaluation, capturing nuances of ligament integrity and ankle stability during movement. Using ultrasonography in dynamic stress tests, such as the anterior drawer and talar tilt tests, provides reliable measurements of ligament laxity, aiding in both diagnosis and surgical planning. This imaging modality can visualize the ligaments in motion, providing valuable information on the ankle joint's degree of laxity and instability. Moreover, ultrasonography demonstrates high diagnostic accuracy in identifying ankle ligament injuries and excels in visualizing anatomical structures with superior spatial resolution. One significant advantage of ultrasonography is its noninvasive and radiation-free nature. This provides a safer alternative to invasive procedures, reduces patient discomfort, and minimizes associated risks. Additionally, the US is a cost-effective imaging solution, making diagnostic evaluations of CAI more accessible than pricier modalities like magnetic resonance imaging. (78, 81, 82)

Although ultrasonography has many advantages, magnetic resonance imaging may provide a different level of detailed soft tissue assessment, possibly selecting image modalities tailored to individual diagnostic needs. Additionally, there are some points to consider when utilizing ultrasonography. Firstly, the operator's expertise is primordial to interpret the exam correctly. Secondly, ultrasonography may have limitations in visualizing deep ankle structures, potentially missing internal pathologies that require deeper penetration. Finally, the patient’s cooperation is vital for a successful examination. (83-85)

8.8.3 Magnetic Resonance

Magnetic resonance imaging provides detailed images of the soft tissues, including ligaments, tendons, and ankle joint cartilage. It can also help differentiate between acute and chronic injuries, assess the extent of damage, and guide treatment decisions. Additionally, magnetic resonance imaging is essential to evaluate associated pathologies, such as osteochondral lesions of the talus, anterior impingement, tendon injuries, and associated syndesmosis ligaments and deltoid ligament injuries that may be present in patients with CAI. These magnetic resonance imaging peculiarities are valuable in diagnosing and managing CAI by providing detailed information on the underlying anatomical structures and pathology. (79, 86,88)

Another possibility is to analyze the ATFL fascicles on magnetic resonance imaging. Studies have shown that a three-dimensional volumetric magnetic resonance imaging modality can identify the ATFL fascicles and the ligament connections (Figure 11). It provides detailed information on their anatomy, structure, and integrity, showing the signal intensity, thickness, length, and appearance of the ATFL fascicles. These radiological studies reinforce the anatomical concepts described in this thesis. Moreover, they leverage new therapeutic possibilities because they help diagnose subtle instabilities currently described as ankle microinstability (22, 89)

Fig 11. Sagittal MRI image showing the (1) superior fascicle of ATFL and (3) inferior fascicle of ATFL with the intervening perforating artery (2). Coronal MRI image illustrating the (2) perforating artery from lateral tarsal branch of the dorsalis pedis artery in the space between the (1) superior fascicle of ATFL and (3) inferior fascicle of ATFL. By Hong et al. (22)

8.8.4 Weight-bearing computed tomography

Weight-bearing computed tomography is a valuable diagnostic tool for assessing foot and ankle pathologies. This method can help diagnose complex deformities related to CAI, especially in cases with subtle hindfoot varus. This information can aid in preoperative planning since varus deformity is related to recurrent lateral ankle sprain. Another applicability of the weight-bearing computed tomography in the lateral ankle sprain is the accuracy in detecting associated lesions, especially injuries to the tibiofibular syndesmosis. These are a frequently overlooked condition that poses challenges for traditional imaging methods due to their complex three-dimensional anatomy and the limitations of conventional two-dimensional radiography imaging. Up to 10% of ankle sprains are estimated to involve associated syndesmotic injuries. Additionally, weight-bearing computed tomography can evaluate the uninjured contralateral side, contributing to evaluating and finding subtle modifications in the ankle joint.(90, 91)

8.9 Conservative Treatment

Conservative measures should be the first line of treatment for lateral ankle sprain. This approach is fundamental to managing acute injuries to the ankle joint without resorting to surgical intervention. While many ankle sprains can be effectively managed through conservative measures, it is essential to understand the principles and strategies involved in this treatment approach. (7)

Conservative treatment options for lateral ankle sprains typically include various forms of immobilization, such as casts, moon boots, or stirrup braces, to stabilize the injured joint and promote healing. Immobilization helps reduce pain, swelling, and further ligament injury, allowing the damaged tissues to repair themselves. Following the initial immobilization phase, a structured rehabilitation program involving different modalities, such as physical therapy exercises, range of motion activities, and proprioceptive training, is often implemented to restore strength, flexibility, and function to the ankle joint. (7)

Physical therapy is crucial to the success of the conservative approach by strengthening the muscles around the ankle, improving joint stability, and enhancing proprioception to prevent future injuries. Manual joint mobilization and manipulation techniques may also improve ankle range of motion, decrease pain, and enhance functional outcomes in acute or chronic lateral ankle sprains. Additionally, modalities like US therapy, cryotherapy, and ankle taping can be beneficial in reducing pain and inflammation, promoting tissue healing, and supporting the injured ankle. While conservative treatment is generally adequate for most acute lateral ankle sprains, it is essential to monitor recovery progress closely. Understanding the importance of early controlled mobilization, proprioceptive balance training, and a comprehensive rehabilitation protocol optimizes the outcomes and prevents recurrent ankle sprains. (74)

The most modern protocol for treating acute and chronic lateral ligament injuries of the ankle is represented by the acronym PEACE and LOVE. (Figure 12) The PEACE protocol focuses on the acute phase of injury management. Critical components of this protocol include ''P'' protecting the injured area, ''E' elevating the ankle to reduce swelling, ''A'' avoiding anti-inflammatory medications, ''C compression to manage edema, and ''E'' educating the patient on early intervention and proper care. The LOVE protocol becomes relevant as the acute phase transitions into the subacute and chronic stages, emphasizing Load, Optimism, Vascularization, and Exercise. Central tenets of the LOVE protocol include progressively loading the ankle for strength and stability, fostering a positive mindset through optimism, promoting vascularization for improved blood flow and tissue healing, and engaging in targeted exercises for function restoration and injury prevention. (92)

Fig 12. ''PEACE'' and ''LOVE'' acronym. (92)

Another tool used in conservative treatment is functional analysis for returning to sports. Return-to-play criteria after conservative treatment of an ankle sprain are essential for overseeing the athlete's recovery progress, minimizing the risk of reinjury, evaluating functional readiness, managing risks, optimizing long-term performance, and providing professional guidance. These structured criteria aid in the safe and effective return to sports activities, fostering optimal recovery, reducing recurrence risks, and enhancing athletic performance in the long run. (56, 60, 74)

The criteria for returning to sports activities after a lateral ankle ligament injury are influenced by injury severity, patient-specific factors, and sports demands. Key considerations include a pain-free range of motion, sufficient strength and stability, ability to perform sports-specific movements, good balance and proprioception, gradual progression through drills, and clearance from a healthcare provider. Athletes should follow a structured rehabilitation program, adhere to return-to-play criteria, progressively increase activity levels, and receive personalized assessment and guidance from healthcare professionals for a safe return to sports participation after a lateral ankle ligament injury. (56, 60, 74)

For optimal effectiveness, a rehabilitation program requires a meticulously structured implementation strategy and thorough monitoring to bolster patient recovery and guarantee adherence to the rehabilitation regimen as they advance through the process. A well-executed conservative treatment significantly enhances the likelihood of successful outcomes. Nevertheless, it is worth noting that around 40% of individuals experiencing acute LCL lesions may eventually develop CAI that could necessitate surgical intervention. (49, 64)

8.10 Surgical Treatment

Several surgical techniques have been proposed to manage lateral CAI. The procedures are divided into anatomic repair with augmentation, anatomic reconstruction with a graft, and nonanatomic reconstruction. Anatomic repair is performed when the ligaments are in suitable condition to be restored without using other tissues to replace them. In this technique, the torn ligaments are tightened, repaired, or reinserted into the fibula with anchors or tunnels to restore adequate tension and joint stability. The repair can be done with a biological or synthetic augmentation in high-demand athletes and patients with high body mass index and hyperlaxity. Anatomic ligament reconstruction uses autogenous grafts due to the poor quality of the native ligaments that are injured beyond the point where primary repair is impossible. Another option is the tenodesis procedure. It is a nonanatomic reconstruction that involves local tendon transfer to provide joint stabilization. (93, 94)

8.10.1 Tenodesis

Tenodesis procedures are commonly used in CAI surgical management, using tendon grafts to augment ankle stability. They are considered when direct primary repair has failed or in cases with risk factors for re-injury. Evans, Watson Jones, and ChrismanSnook described the most traditional tenodesis techniques in the literature. (7, 50, 95)

The Evans technique involves using the peroneus brevis tendon, passed through a drill hole in the distal fibula, and fastened under tension to create a solid autogenous lateral ligament of the ankle. While the Evans procedure could provide mechanical stability to the ankle, it may not always lead to a total return of pre-injury function. Additionally, ligament laxity often recurs five years post-Evans tenodesis, leading to impaired ankle range of motion and swelling, indicating potential functional limitations. (7, 50, 95)

Watson Jones's tenodesis involves harvesting a tendon graft, usually from the peroneus longus or brevis muscle. This tendon is then split and rerouted to reconstruct the lateral ligaments of the ankle. The graft is anchored to the fibula and talus to stabilize the ankle joint. A modified version of the procedure may be employed, which uses a split of the peroneus longus or brevis muscle to enhance the biomechanical stability of the ankle. Studies have shown that the Watson-Jones procedure can effectively fixate the talus and prevent loss of subtalar movement, making it a favorable choice for addressing ankle instability. However, long-term follow-up studies have indicated that the Watson-Jones procedure, along with other tenodesis techniques like the Evans surgery, may lead to gradual deterioration over time, including issues such as postoperative loss of range of motion, recurrence of instability, ankle pain under stress conditions, and increased radiographic arthritic changes Finally, the ChrismanSnook procedure involves using one-half of the peroneus brevis tendon, routed through tunnels in the fibula and calcaneus, to reconstruct the ATFL and CFL.

This method aims to restore stability to the ankle by mimicking the function of the damaged ligaments. Biomechanical studies have demonstrated that the ChrismanSnook technique provides better stability than other procedures like the Evans technique, particularly in the early stages of ankle joint restoration. Despite its effectiveness, the Chrisman-Snook procedure does not fully restore normal ankle kinematics. Studies have shown that while it reduces neutral zone laxity, it does not entirely normalize ankle flexibility, which may explain some adverse clinical reports. (7, 50, 94, 95)

8.10.2 Broström - Gould Repair

The most classical procedure, the Broström repair, was first described in 1966.(96) Since then, this procedure has been studied and evolved. It is a simple procedure that involves a direct open repair of the ATFL and CFL, reattaching these ligaments on the lateral malleolus through transosseous fixation. Several surgeons demonstrated satisfactory functional outcomes with a low rate of complications in the literature, reinforcing the reproducibility of this procedure. The results were less acceptable in patients with generalized hyperlaxity or more than ten years of ankle instability. Later, in 1980, Gould et al. reported a modification to the Broström technique in which the lateral ankle ligaments were strengthened by pulling the extensor retinaculum proximal and suturing it to the distal fibula.(97) This reinforces the ATFL repair and limits inversion to stabilize the subtalar joint. This modification has been shown to increase the strength of the repair by 50%. The ligament repair with the IER augmentation, named Broström -Gould, was popularized in 1993 by Hamilton and colleagues after successful outcomes in professional ballet dancers. Subsequent studies have shown that incorporating the IER could improve the biomechanical strength of the repair by 60%. (94, 98)

Despite the good functional outcomes and ankle stability restoration with the open Broström Gould procedure, a group of patients had residual pain, aching, swelling, and crepitation symptoms. These worst results were analyzed, and a high incidence of associated intraarticular lesions such as synovitis, loose bodies, ossicles, chondral lesions, osteochondral lesions of the talus, adhesions, and osteophytes was discovered.(99) This data suggested that failure to treat the intra-articular pathology could result in a symptomatic ankle despite stable repair of the lateral ligaments.

Considering this, the surgeons performed an ankle arthroscopy before the ligament repair to recognize and treat the associated intraarticular pathologies. This new approach showed better results and highlighted the importance of ankle arthroscopy in patients with CAI. (100, 101)

8.10.3 Ankle Arthroscopy

Ankle arthroscopy is performed using two leading portals: anteromedial and anterolateral. The anteromedial portal is created first. The portal is placed just medial to the tibialis anterior tendon, at the ankle joint line, or slightly proximal. This portal was regarded as the vision portal, and arthroscopic exploration was carried out with the arthroscope introduced through it. (Figure 13)

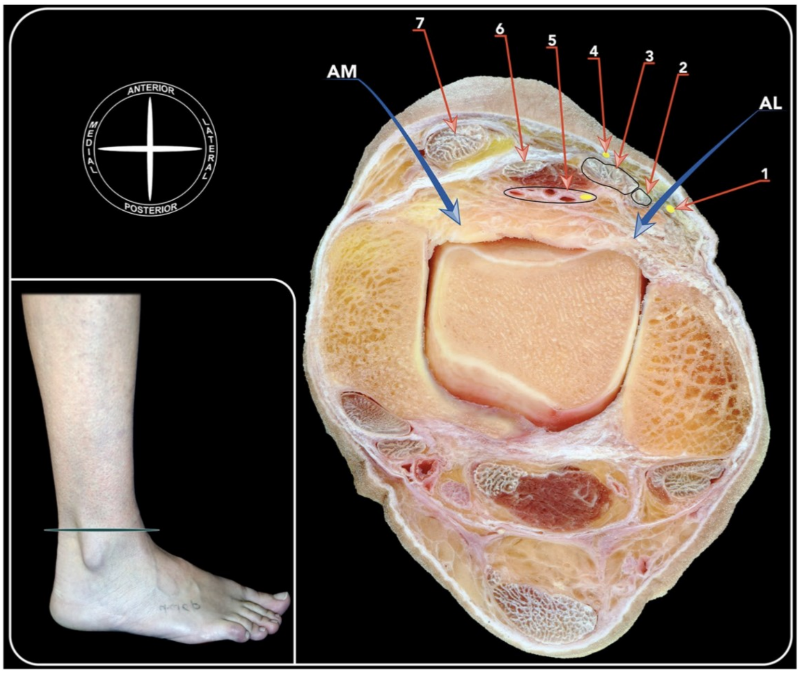

Fig.13 Transverse section at the level of the tibiotalar joint showing the position of the anterior portals and structures at risk. AM: Anteromedial portal. AL: Anterolateral portal. (1) Dorsal intermediate cutaneous nerve (branch of the superficial peroneal nerve, highlighted in yellow). (2) Peroneus tertius tendon. (3) Extensor digitorum longus tendon. (4) Dorsomedial cutaneous nerve (branch of the superficial peroneal nerve, highlighted in yellow). (5) Anterior neurovascular bundle (anterior tibial artery and accompanying veins, deep peroneal nerve). (6) Extensor hallucis longus tendon. (7) Tibialis anterior tendon. By Malagelada et al. (102)

A standardized arthroscopic exploration is performed in each compartment (anterior, central, and posterior). (Figure 14) Once the anteromedial portal is established, the anterolateral portal is created using a similar technique. This portal is regarded as the working portal for the introduction of instruments. It can be placed lateral to the peroneus tertius tendon and the extensor digitorum longus tendons and medial to the superficial peroneal nerve (SPN). (103, 104) Complication rates for anterior ankle arthroscopy have been reported to be up to 17 %, of which more than 25 % was related to iatrogenic SPN damage during anterolateral portal placement. (105) The SPN perforates the crural fascia at an average of 13 cm proximal to the level of the ankle joint. Subsequently, the nerve divides into its terminal branches: the medial dorsal cutaneous and the intermediate dorsal cutaneous nerves. Identifying the SPN helps avoid this structure during the anterolateral portal dissection. The SPN visualization can be improved with the ankle in plantar flexion and inversion. (106)

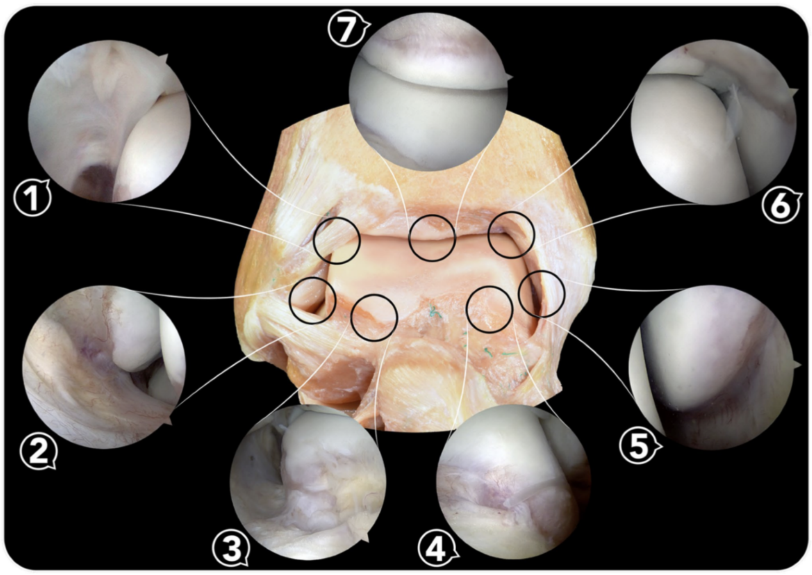

Fig 14. Anterior ankle arthroscopic anatomy: a 7-point examination protocol for the anterior ankle compartment using dorsiflexion and non-distraction technique, and arthroscope introduced through the anteromedial portal. 1. Home position (ATiFL's distal fascicle). 2. Lateral gutter (ATFL's superior fascicle, resident's fibular tip). 3. Lateral talar neck. 4. Medial talar neck. 5. Medial gutter (deep layer of deltoid ligament, anterior tibiotalar ligament, the tip of the medial malleolus). 6. Medial tibial angle (notch of Henry). 7. Anterior tibial rim. By Vega et al. (107)

Different techniques for joint access can be used for ankle arthroscopy, including distraction and dorsiflexion. Each method has distinct advantages and considerations that impact surgical outcomes and patient safety. In the distraction method, the ankle joint is distracted or pulled apart, creating space between the joint surfaces. This space provides excellent visualization of the central compartment, making it easier to treat osteochondral lesions, remove loose bodies, and asses the syndesmosis. The inconvenience is that it requires specialized distraction equipment, such as a distraction frame or ankle distractor, which may add complexity and time to the procedure. In addition, excessive distraction can lead to the excessive stretching of soft tissues, making it challenging to analyze ligaments and increasing the risk of neurovascular injuries. The dorsiflexion method is a more straightforward approach that does not require specialized distraction equipment. The dorsiflexion method provides a more extensive and safer anterior working area than the distraction method, as it moves neurovascular structures away from the surgical site. Additionally, it allows constant visualization of the ATFL sup on the floor of the lateral gutter, the ATIFL's distal fascicle laterally, and the anterior margin of the deltoid ligament in the medial gutter. (108)

The use of ankle arthroscopy started to assist in repairing lateral ligaments. Hawkins (109) reported the first arthroscopic ankle stabilization in 1987 using a staple technique to plicate the lateral ankle ligaments. They showed promising results with only one recurrence; the remaining complications were attributed to staple prominence. Afterward, Kashuk and colleagues described the first arthroscopic technique, which used suture anchors to repair the lateral ligaments. With the evolution of ankle anatomy knowledge and technology, dedicated ankle arthroscopic instruments were developed, and the arthroscopic lateral ligament repair techniques have been continuously refined over the years. (94, 110)

8.10.4 Arthroscopic Broström

To reproduce the good results of the open Brostrom Gould procedure, some authors developed the arthroscopic Broström (AB).(94, 111) It is a percutaneous technique with arthroscopic assistance. The method entails arthroscopic insertion of anchors into the fibula and a percutaneous step to stitch the lateral ligament and the IER. Although this procedure is not fully arthroscopic, it was an essential milestone in the evolution of arthroscopic repair techniques. The AB showed similar clinical and biomechanical outcomes compared to the open Broström Gould. Beyond that, the long-term follow-up studies showed that the patients maintained their level of sports activities.

Therefore, it shows a high rate of reported complications (5.3%-29%) due to neurological entrapment or prominent implants. (112)

Additionally, using the IER as a biological reinforcement for ligament repair remains controversial. (113) The IER is a thickening of the anterior part of the crural fascia at the ankle level. This aponeurotic structure holds the tendons of the anterior compartment of the leg against the bone, preventing bowstringing and subluxation. Furthermore, the anatomical proximity of the oblique superolateral band of the IER to the SPN is another factor to consider before augmentation with this structure. (114)

8.10.5 Arthroscopic All-Inside Repair

With the advancement of ankle anatomical knowledge and arthroscopic instruments, the arthroscopic techniques for ankle ligament repair continued developing. Some surgeons developed an anatomical and all-inside arthroscopic procedure. The arthroscopic all-inside repair of the lateral ligaments of the ankle is a fully arthroscopic and anatomical technique designed to assess CAI. This procedure involves repairing the lateral ligaments of the ankle joint using arthroscopic guidance, allowing for precise and targeted repair of the damaged ligaments. (115) The technique typically involves repairing the ATFL and CFL using an all-inside approach. (Figure 15) Indications for arthroscopic all-inside repair of the lateral ligaments of the ankle include chronic ankle instability, recurrent ankle sprains, and ligament laxity that has not responded to conservative treatments. (115).

The arthroscopic all-inside repair is particularly beneficial for patients who require a minimally invasive approach with reduced postoperative recovery time and an earlier return to daily activities and sports. (41) This technique offers several advantages, including improved visualization of the ankle joint structures, reduced risk of neurological complications, and the ability to address concomitant intra-articular pathologies. Despite this, some surgeons have criticized using anatomical techniques that do not involve the IER. (94) Furthermore, the all-inside arthroscopic ATFL repair is a technically challenging and still recent procedure. The original centers of this technique showed excellent results; (116) therefore, there is a lack of a series of cases and comparative studies with other arthroscopic procedures.

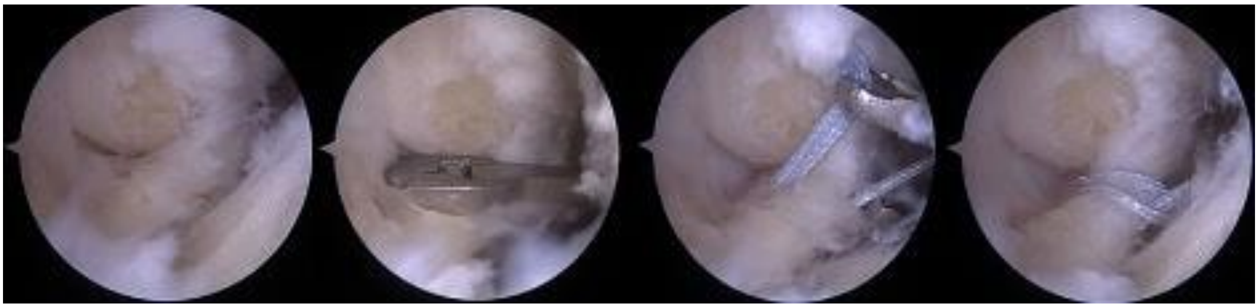

Fig. 15. Arthroscopic All Inside Repair. *Author's archive*

Additionally, this approach allows for anatomical repair of the lateral ligaments, leading to better restoration of ankle stability and function (117). However, despite the advantages of all-inside ATFL repair, there are limitations associated with the remnant tissue quality. Patients with hyperlaxity, high body mass index, insufficient ligament, and poor quality of local tissue have been identified as poor prognostic factors for anatomic repair, potentially leading to a relatively high recurrence rate after arthroscopic ATFL repair. (43, 113) Additionally, the condition of the ATFL remnants is crucial as it is associated with the reparability of the ligament, highlighting the importance of adequate tissue quality for successful outcomes. (Figure 16) In these cases, adding some augmentation for the ligament repair or performing reconstruction with a tendon graft is necessary. (43, 118)

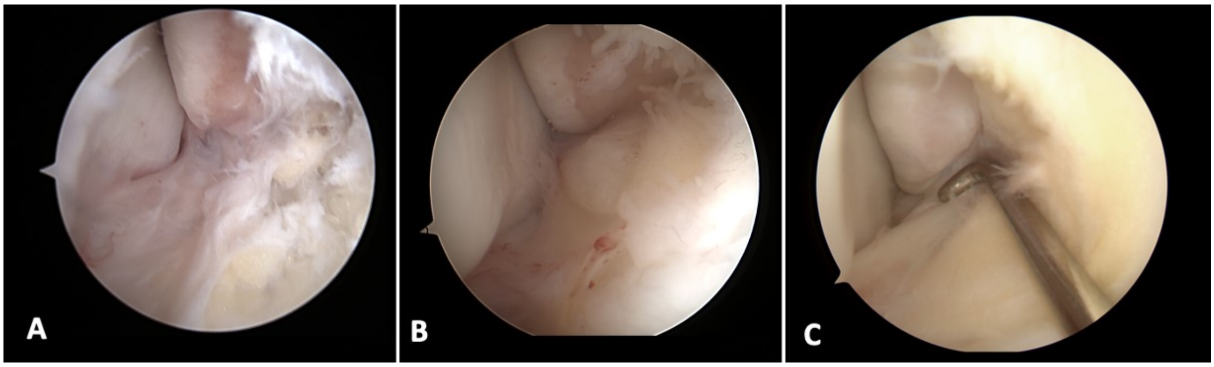

Fig 16. Arthroscopic ATFL quality assessment. (A) Partial ligament detachment (B)Total ligament detachment (C) Hook palpation. By Nunes et al. (119)

8.10.6 Arthroscopic All-Inside Repair with Biological Augmentation

Considering the limitations of isolated all-inside repair, techniques with augmentation of the lateral ligaments have emerged as a sophisticated and minimally invasive surgical option for treating CAI. After repairing the ligaments arthroscopically, biological tissue can be used to reinforce the repaired ligaments. (Figure 17) All-inside with biological augmentation involves an endoscopic approach to grasp and fix the IER in the same suture of the ligaments. (21) Although IER is used every day and has been used for many years, its usefulness and feasibility have been questioned. The first reason is that the IER is an aponeurotic tissue continuous with the sural fascia, and its limits are not always clear, leading to a subjective surgical assessment of the structure. Biomechanical tests found that incorporating the IER in the traditional Broström repair had no mechanical advantage. (98, 114)

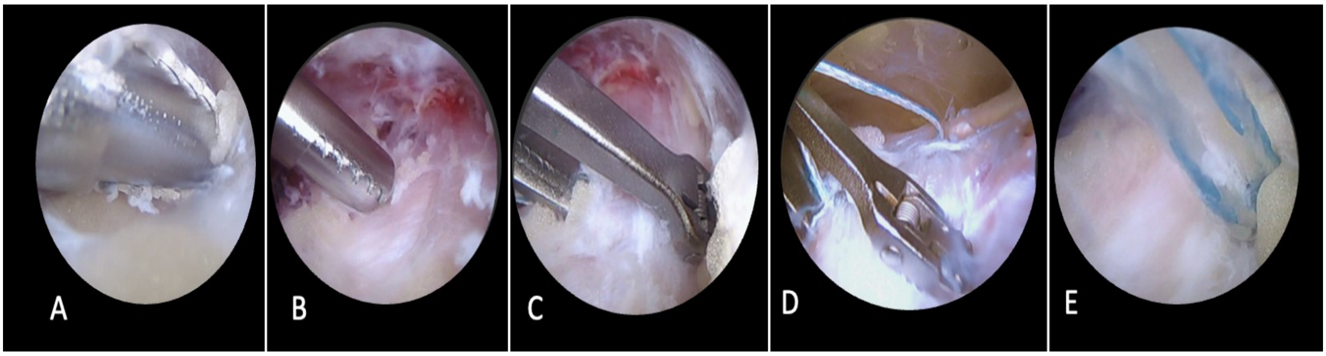

Fig 17. Arthroscopic all-Inside repair with biological augmentation. By Nunes et al. (119)

Another possibility of biological augmentation for lateral ligament repair is using the ATIFL. This arthroscopic procedure involves transferring the ATIFL from its tibial origin to the talus. It provides biological and strength reinforcement, increasing ankle stability. From an anatomical perspective, the distal fascicle of the ATIFL and the ATFL sup have standard features, including their intra-articular position, contiguous fibular origins, and comparable length and width. The technique is challenging and demands advanced arthroscopic skills. (120)

8.10.7 Arthroscopic All-Inside Repair with Non-Biological Augmentation

Another possibility is the use of non-biological augmentation. The all-inside technique with non-biological augmentation, known as the internal brace, innovated ankle stabilization by utilizing a suture tape anchored to the talar insertion of the ATFL.

(Figure 18) This procedure effectively mitigates the risk of recurrent ankle instability, which is particularly beneficial in cases with compromised ligament quality, hyperlaxity, or elevated body mass index. The literature consistently highlighted remarkable enhancements in ankle stability, pain alleviation, and overall functional capacity. Patients experience a significant return to pre-injury activity levels, minimal recurrence rates, and high satisfaction with their outcomes. Moreover, the augmentation reinforces confidence in pursuing aggressive rehabilitation strategies and expedites the recovery timeline for a swift return to sports engagement. (43, 121)

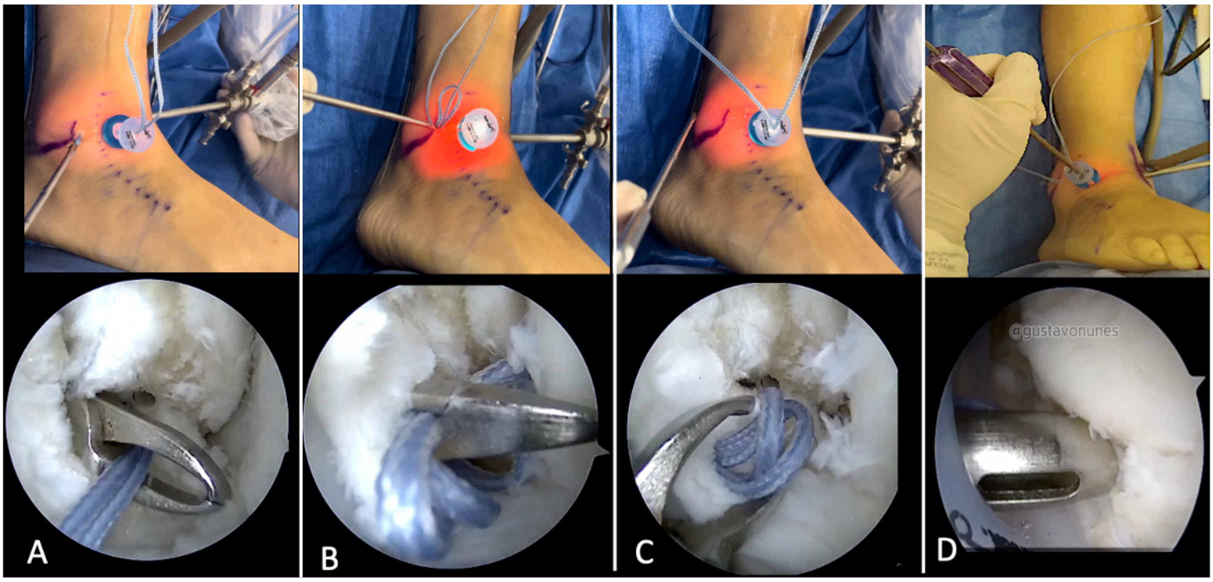

Fig 18. Arthroscopic all-Inside repair with non-biological augmentation. By Nunes et al. (119)

8.10.8 Endoscopic Reconstruction

Anatomic lateral ankle ligament reconstruction uses an autograft or allograft tendon to replace the ligaments and restore ankle stability and function. (103) The most common graft harvested is the gracilis tendon. (Figure 19) This procedure is preferred to treat CAI in cases where primary repair, mainly severe ligament compromise or revision, cannot be performed. Advantages of lateral ankle ligament reconstruction with a gracilis tendon graft include restoring ankle stability, improved functional outcomes, and preventing long-term complications. (118) This procedure can achieve satisfactory surgical outcomes and facilitate a return to sports activities for high-demand patients with CAI with a low complication rate. However, arthroscopic reconstruction is technically demanding, more morbid, with a donor site morbidity, and requires more excellent patient recovery than arthroscopic repair. Nonetheless, the complication rate of arthroscopic reconstruction is still low. (43)

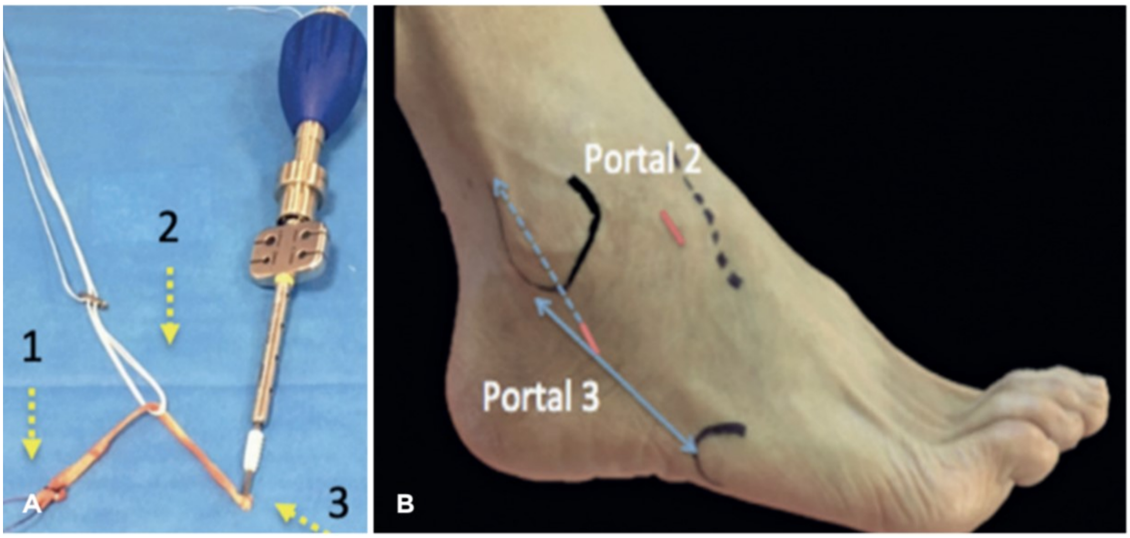

Fig 19. (A) Gracilis graft. (1) Calcaneal side with suture wire; (2) Fibular side with adjustable endobutton; (3) Talar side with tenodesis screw (B) Arthroscopic portals to lateral ligament reconstruction. By Nunes et al.(119)

9. Hypothesis

1. The connection between ATFLinf and CFL is a structure that can transmit tension between these ligaments.

2. A tridimensional analysis can clarify the connections and footprints of the lateral ligaments of the ankle.

3. All-inside ATFL repair is a reproducible procedure for treating CAI. It achieves good clinical and functional results with a low rate of complications.

4. All-arthroscopic techniques have better clinical results than arthroscopic-assisted techniques in treating CAI.

10. Objectives

1. The objective is to conduct a dynamic analysis of the connecting fibers and to ascertain their strength in transmitting tension between the ligaments they connect.

2. The objective is to carry out an analysis of the footprints of the lateral ankle ligaments and their interrelationships through a three-dimensional view utilizing a white structured light scanner.

3. The objective is to compare the preoperative and postoperative clinical and functional outcomes of a group of patients with chronic ankle instability who underwent all-inside arthroscopic ATFL repair.

4. The objective is to compare the clinical outcomes of the all-arthroscopic technique with those of the arthroscopic-assisted technique in the treatment of chronic ankle instability.

11. Material, Methods, and Results

The following publications report the material, methods, and results of the studies published studies in scientific journals:

1. Cordier G, **Nunes GA**, Vega J, Roure F, Dalmau-Pastor M. Connecting fibers between ATFL's inferior fascicle and CFL transmit tension between both ligaments. *Knee Surgery, Sport Traumatol Arthrosc*. March 2021:21-26.

2. **Nunes GA**, Martinez LM, Cordier G, Michels F, Vega J, Moreno RS, DalmauPastor M. The ATFL inferior fascicle, the CFL, and the PTFL have a continuous footprint at the medial side of the fibula. Knee Surg Sports Traumatol Arthrosc. 2023 Sep 2.

3. **Nunes GA**, Ferreira GF, Caetano RM, Mann TS, Guelfi M. All-inside arthroscopic anterior talofibular ligament repair: a case series. Int Orthop. 2022 Feb;46(2):273-279.

4. Guelfi M, **Nunes GA**, Malagelada F, Cordier G, Dalmau-Pastor M, Vega J. Arthroscopic Assisted Versus All-Arthroscopic Ankle Stabilization Technique. *Foot Ankle Int*. 2020;41(11):1360-1367.

Knee Surgery, Sports Traumatology, Arthroscopy
https://doi.org/10.1007/s00167-021-06496-w

ANKLE

Connecting fibers between ATFL's inferior fascicle and CFL transmit tension between both ligaments

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Abstract

Purpose The lateral ligament complex of the ankle has been extensively studied. Recently an anatomical study described a connection between anterior talofibular ligament inferior fascicle (ATFLif) and calcaneofibular ligament (CFL). The applicability and the mechanical role of these connections have not yet been studied and need to be clarified. The purpose of this study is to evaluate the connection between ATFLif and CFL through a dynamic measurement analysis.

Methods An anatomical study was performed in 13 fresh-frozen below-the-knee ankle specimens. Each specimen was dissected in a protocolized manner until the lateral ligaments were exposed. A complete injury to both ATFL's fascicles was created in the proximal third of the ligament. A displacement transducer specifically design was inserted in the CFL and in the lateral part of the calcaneus to test its lengthening. A traction of 1 kg weight (9.8 N) was applied to ATFLif while the transducer measured the lengthening that this force created in the CFL.

Results A total of 13 ankle specimens were carefully dissected. One specimen with signals of a prior traumatic injury of the ATFLif was excluded. A total of 12 specimens were included, 7 females and 5 males with an average age of 74 years (52–88 years). The right ankle was dissected in 6 specimens.

ATFL was identified as a two-fascicled ligament in all cases. The fibers connecting the ATFLif and CFL were observed in all specimens. The displacement transducer showed lengthening in the CFL in all measurements with a median of 0.59 mm (SD $\pm$ 0.34).

Conclusion Connecting fibers between ATFLif and CFL are robust enough to transmit tension from one structure to the other. In the case of associated proximal lesions of the ATFLif and CFL, ligaments repair with a single suture may be considered. This can be applied in surgical procedures in patients with lateral ankle instability.

Keywords Anatomy · Ankle · Ankle lateral ligaments · Anterior talofibular ligament · Calcaneofibular ligament · Lateral ligament repair

Introduction

An increasing interest in chronic ankle instability (CAI) has been recently observed [3, 4, 13, 24, 25, 29]. Studies describe that CAI occurs after approximately 20% of ankle sprains and must be surgically treated if conservative treatment fails [18, 19, 22, 23, 26, 27]. Surgical procedures aiming to treat CAI have significantly evolved in recent years. Literature has confirmed the superiority of anatomical techniques over the non-anatomical [10, 30].

Regardless of previous studies, it is well established that the anterior talofibular ligament (ATFL) is usually formed

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by two separate fascicles [9]. Vega et al. [28] showed the anatomical differences between both fascicles: ATFL's superior fascicle (ATFLsf) is an intra-articular structure, while ATFL inferior fascicle (ATFLif) is an extra-articular one. Connections were found between ATFLif and the calcaneofibular ligament (CFL). Therefore, the concept of the lateral fibulotalocalcaneal ligament (LFTCL) complex was proposed: an anatomical isometric structure composed by the ATFLif, the CFL, and their connecting arciform fibers [28] (Fig. 1). Recently Dalmau et al. [5] described anatomical medial connections between the components of the lateral collateral ligament (LCL) complex, further reinforcing the concept of a functional unit where the ATFL, CFL and the posterior talofibular ligament (PTFL) are connected.

Understanding the mechanical relationships between the components of the LCL is important for the pathogenesis, diagnosis and treatment of CAI. When a surgical treatment is needed for, the LFTCL complex as a functional unit with connections between their components would suggest that a single act on one of their components will have an effect on the other components [28]. However, at this point, it is unknown whether the connecting fibers are robust enough to transmit tension from ATFLif to CFL. Biomechanical

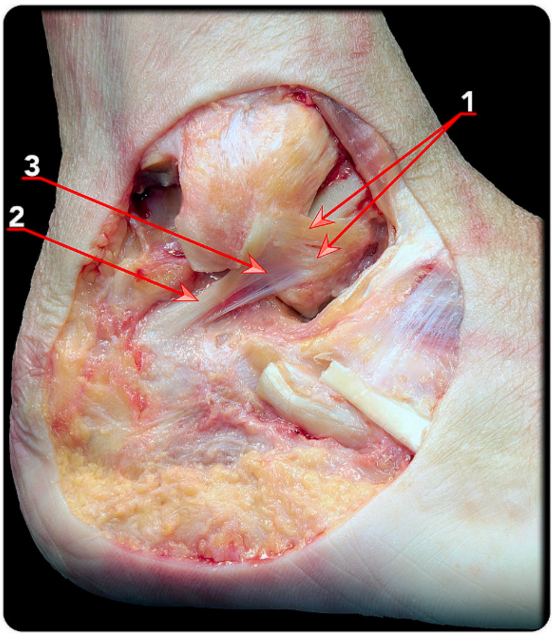

Fig. 1 Anatomical dissection used to perform this study. An anterolateral skin window was created, and plane-by-plane dissection advanced until ATFL and CFL were observed. Attention was paid to observe the longitudinal pattern of the ligamentous fibers to ensure adequate dissection was performed. 1. ATFL's superior and inferior fascicles, 2. CFL, 3. Fibers of the Lateral Fibulotalocalcaneal Ligament Complex connecting ATFL's inferior fascicle and CFL

features of this connection need to be clarified validating the clinical applicability of the LFTCL. ATFLif transmitting tension to CFL could be a possible explanation of the good results achieved by Maffuli et al. [14] treating an injury of both ATFL and CFL by an isolated ATFL repair.

The purpose of this study was to evaluate the ability of the connecting fibers between ATFLif and CFL to transmit tension between them through a dynamic measurement analysis. It is hypothesized that the connection between ATFLif and CFL can transmit the tension to CFL when the ATFLif is under traction, and therefore provoke its lengthening.

Materials and methods

The anatomical study was approved by the ethical committee of the University of Barcelona with IRB number 00003099. A total of 13 fresh-frozen ankle specimens were provided by and dissected at the Anatomy Department of the University of Barcelona (Spain). The data including the specimen's descriptions (specimen identification, age, sex, and side) and the CFL lengthening measurement were recorded to the analysis. Exclusion criteria for the study included: specimens with any foot and ankle deformities, cutaneous incisions that suggested any foot and ankle surgery or trauma and ATFL or CFL injury observed during dissection.

Each specimen was dissected in a protocolized manner. An experienced anatomist in foot and ankle performed all the dissections [6]. After thawing the specimens by submersion in room temperature water, they were placed in a lateral position and fixed to the dissection table with two k-wires avoiding any undesired movement. One K-wire transfixed the distal third of the fibula and tibia, and another transfixed the center of the calcaneus.

An anterolateral skin window was created and a plane-by-plane anatomical dissection was performed until the anterolateral ankle joint capsule was reached. At this point, the capsule was carefully dissected off the LCL to expose them. After dissection of the LCL, the specimen was inspected to check if ATFLif and CFL were intact. To assess the quality of the ligament tissue, the dissection was advanced until the longitudinal fiber pattern of the ligament was clearly observed, as not doing so would be a bias both for the morphology of the ligament and for its quality (Fig. 1).

With the ankle dissected and the LCL exposed, the transmission of tension between the ATFLif and CFL was measured by means of a purpose-designed and build displacement transducer (Fig. 2). The transducer consists of a U-shaped piece of high-grade steel strip, 1 mm thickness and 10 mm width. The height of the transducer is 20 mm and the length are 40 mm. Both free ends of the flanges have been machined to give them the form of an acute spike, so they can be introduced easily in the point of the

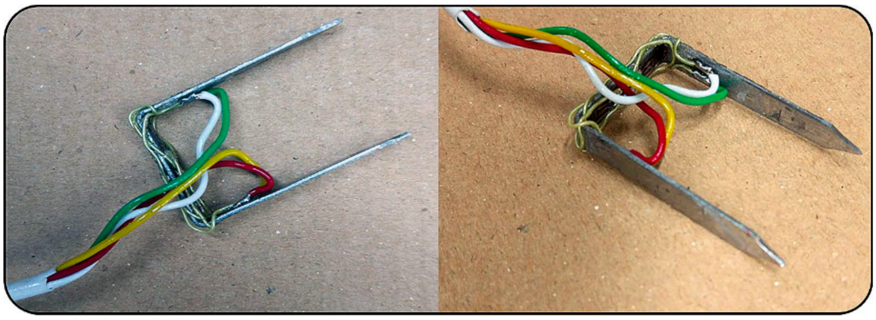

Fig. 2 U-shaped transducer used in the study. A U-shaped piece of high-grade steel strip with four strain gauges bonded to it, which allows deformation of the steel strip to be measured

ligament whose tension wants to be measured. Four strain gauges have been bonded to the web of the transducer, two on each side, and connected to form a whole Wheatstone bridge. When the ligament deforms, the distance between the points of insertion of the transducer changes, and the transducer is obliged to deform. The deformation of the steel strip of the transducer is passed to the strain gauges bonded to it, whose electric resistance varies proportionally to the deformation. The variation of electric resistance is transformed in the variation of voltage, which is ridden by an interface and feed to the computer, where it is stored. The relation within the relative displacement of the two points of the transducer and the variation of voltage measured is linear. The transducer has been calibrated up to a displacement of 2 mm, with a linearity better than 0.01 mm.

With a scalpel blade, a complete injury for both ATFL's fascicles was performed in the proximal third of the ligament, trying to mimic the most commonplace of injury, its fibular attachment [14]. A straight mosquito clamp grasped the part of the ATFL that remained attached to the fibula. Using a K-wire, a small hole was created on the lateral side of the calcaneus and used as a fixation point to one end of the steel strip of the transducer. The other end of the steel strip of the transducer was inserted in the middle of CFL (Fig. 3). With this setup, any lengthening created on the CFL could be measured, as the transducer displacement was oriented in the same longitudinal direction that the CFL.

The traction on ATFLif was obtained through 1 kg weight (9.8 N), applied with the help of a manometer connected to the mosquito clamp (Fig. 4). The traction was applied on the mosquito clamp and the displacement transducer measured the lengthening induced in the CFL.

Fig. 3 One steel strip of the transducer was inserted in CFL and one in the lateral side of the calcaneus

Statistical analysis

Statistical analysis was performed using SPSS 23 (SPSS Inc., Chicago, IL, USA). The data were analyzed descriptively using median, and standard deviation.

Results

A total of 13 ankles specimens were carefully dissected. One specimen was excluded because a single ATFL fascicle with a synovialized appearance, suggesting a prior traumatic injury of the ATFLsf was found. There was a total of 12 specimens included, 7 females and 5 males with a median age of 74 (52–88) years. The right ankle was dissected in 6 specimens.

After dissection, no morphological anatomical variation was observed in any specimen. The ATFL was identified as a two-fascicled ligament with an evident gap filled with fatty fibrous tissue between both fascicles in all cases.

Regarding the footprint, all specimens presented a common footprint for ATFLif and CFL located at the anterior aspect of the lateral malleolus, proximal to the fibular tip,

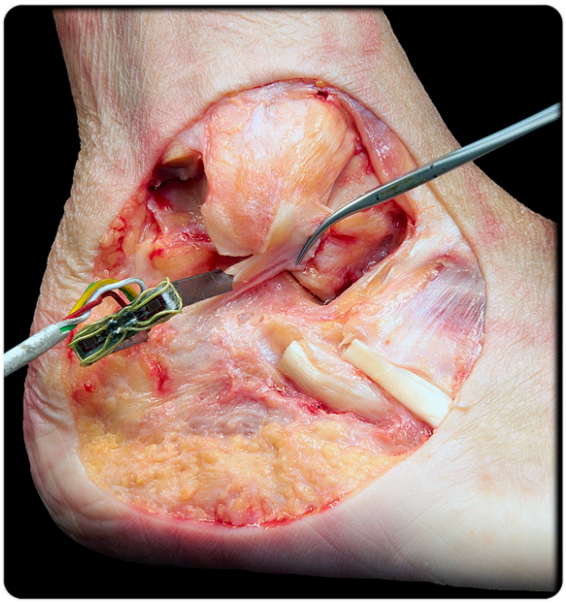

Fig. 4 A complete injury to both ATFL's fascicles was created, and a mosquito clamp grasped the fibular attachment of ATFL. Traction was applied with a manometer to apply 1kg of tension

and just below the fibular insertion of the ATFLsf. The talar insertion of ATFLif was localized at the talar neck just below the talar insertion of the ATFLsf fascicle. The fibers connecting the ATFLif and CFL was observed in all specimens of this study.

During ATFLif traction the transducer showed lengthening of CFL in all measurements. The median of the measurement was 0.59 mm (SD $\pm$ 0.34; 0.42–1.35).

Discussion

The most important finding of this research is that tension is transmitted to CFL provoking its lengthening when traction is applied to the ATFLif. The clinical relevance of this study is that the connecting fibers between ATFLif and CFL could effectively be used to indirectly repair CFL through ATFLif reattachment.

Connections between components of the LCL complex have been reported by several authors over the year [5, 12, 26, 28]. A 3-dimensional computed tomography imaging study showed that CFL and ATFLif sharing a single confluent footprint on the distal border of the fibula [18]. In addition, Matsui et al. [15] reported that the fibular obscure tubercle can be used as a bone landmark representing the point of intersection of the ATFL and CFL footprint. Kakewaga et al. [12] dissected 60 ankles and found connections between ATFL and CFL in all of them. Interpretation about this anatomical structure was later clarified by Vega et al. They exposed that ATFLif and CFL are isometric ligaments, connected by arciform fibers, forming the LFTCL complex [28]. The anatomical findings of the current study reinforce the LTFCL complex description and validate this concept showing that the connection is able to transmit the tension to CFL and provoke its lengthening when ATFLif is under traction.

The anatomic variations of the lateral talocalcaneal ligament (LTCL) have been related to the connections between ATFLif and CFL in several studies [2, 12, 31, 32]. A recent anatomical study suggests that some CFL variations may also be part of this complex [21]. In the current study, the arciform fibers between ATFLif and CFL have been observed in all specimens.

As suggested by the results obtained in the current study, arciform fibers are strong enough to transmit tension between the ATFLif and CFL. Because of the transmission of tension, a lengthening was obtained in all CFL's measurements during traction on ATFLif. As a result, in the case of a lateral ankle sprain, the energy of the injury will be also transmitted from one to the other ligament. Although it was not studied in the presence of an injury to the ATFLif observed on imaging studies will indicate a probable injury to the CFL.

These findings support the good clinical results of isolated ATFL repair techniques in cases of CAI and injury of both ATFL and CFL [14]. Connections between ATFL and CFL are probably robust enough to stabilize the ankle after ATFL repair. However, no clinical or mechanical studies in relation to subtalar joint instability secondary to CFL injury have been reported after treating isolated ATFL. More studies are required to highlight this aspect.

Arthroscopic techniques are gaining popularity to treat CAI. Several arthroscopic ATFL repair procedures have been published [1, 7, 8, 16, 17, 20, 25]. Guelfi et al. [11] demonstrated through an anatomical study the possibility grasping one or two fascicles of ATFL during an arthroscopic anatomical repair depending on the suture passer used to penetrate the ligament.

This is the first study to dynamically investigate connecting fibers between ATFLif and CFL. As demonstrated, connections between ATFLif and CFL play an important functional role. When traction on the ATFLif, tension is transmitted to CFL, and CFL suffers a lengthening. This suggest that an isolated ATFL repair will be enough to restore the ankle stability when injury of both, CFL and ATFL. Therefore, the applicability of the results of this study is only valid if the CFL lesion occurs proximally conserving the common fibers.

The present study was limited by the fact that a small number of specimens were included. Probably a larger series would improve the validity of this research. Although the objective of the study was just to prove that movement transmission occurs through the connection, we do not know how much strength is necessary to achieve it (although 1 kg weight—9.8 N—was enough in this study), and how this will clinically translate to the patient in the surgical setting, where tissue quality could affect the movement transmission. Finally, ankles without laxity were used for this research to test the normal connection of the lateral ligament complex which may differ in pathological cases.

Conclusion

In conclusion, connecting fibers between ATFLif and CFL play a mechanical role. As demonstrated, connecting fibers are robust enough to transmit tension from ATFLif to CFL. In the case of associated proximal lesions of the ATFLif and CFL, ligaments repair with a single suture may be considered. This can be applied in surgical procedures in patients with lateral ankle instability.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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ANKLE

The ATFL inferior fascicle, the CFL and the PTFL have a continuous footprint at the medial side of the fibula

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Abstract

Purpose Knowledge of the complex anatomy of the lateral ankle ligaments is essential to understand its function, pathophysiology and treatment options. This study aimed to assess the lateral ligaments and their relationships through a 3D view achieved by digitally marking their footprints.

Methods Eleven fresh-frozen ankle specimens were dissected. The calcaneus, talus and fibula were separated, maintaining the lateral ligament footprints. Subsequently, each bone was assessed by a light scanner machine. Finally, all the scans were converted to 3D polygonal models. The footprint areas of the talus, calcaneus and fibula were selected, analysed and the surface area was quantified in cm^2.

Results After scanning the bones, the anterior talofibular ligament inferior fascicle (ATFLif), calcaneofibular ligament (CFL) and posterior talofibular ligament (PTFL) footprints were continuous at the medial side of the fibula, corresponding to a continuous footprint with a mean area of 4.8 cm^2 ($\pm$0.7). The anterior talofibular ligament (ATFL) footprint on the talus consisted of 2 parts in 9 of the 11 feet, whilst there was a continuous insertion in the other 2 feet. The CFL insertion on the calcaneus was one single footprint in all cases.

Conclusion The tridimensional analysis of the lateral ligaments of the ankle demonstrates that the ATFLif, CFL and PTFL have a continuous footprint at the medial side of the fibula in all analysed specimens. These data can assist the surgeon in interpreting the ligament injuries, improving the imaging assessment and guiding the surgeon to repair and reconstruct the ligaments in an anatomical position.

Keywords Anatomy · Ankle · Anterior talofibular ligament · Calcaneofibular ligament · Posterior talofibular ligament · Ankle lateral ligaments

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Introduction

The lateral ankle ligaments are the most common musculoskeletal injured structures in the physically active population [8, 16]. A single ankle sprain results in chronic symptoms in approximately 10% of all patients [14]. The lateral ligaments of the ankle are composed of the anterior talofibular ligament (ATFL), the calcaneofibular ligament (CFL) and the posterior talofibular ligament (PTFL) [5, 7].

A thorough knowledge of the anatomy of the ankle ligaments is essential for different aspects. First, it is necessary to improve understanding of the pathophysiology of chronic lateral ankle instability (CAI) [2, 4]. CAI is a complex entity in which different types of injuries may be encountered, resulting in other consequences for the patient [7, 19]. Second, the normal anatomical aspect of the ligaments should be used as a reference when interpreting injury patterns during the diagnostic assessment [7, 9]. The diagnosis assessment includes imaging tools such as ultrasound, MRI and perioperative evaluation of the injuries [9, 12, 18, 20]. Finally, anatomical descriptions are essential in treatment when performing surgical repair or reconstruction of the ligaments as we strive to restore typical anatomical properties [4, 10].

Although earlier literature assessed the anatomy of the lateral ligaments of the ankle, many aspects remain unknown [2, 4, 5, 10, 17]. Most anatomical studies of the lateral ligaments focussed on analysing their length, width and bone landmarks. They were carried out in a 2D view with a digital calliper or goniometer [6, 10, 11, 23, 24]. More recent publications demonstrated that this anatomical region is far more complex [2–4, 20, 21]. These studies demonstrated that two fascicles predominantly form the ATFL, and its inferior fascicle shares the footprint with the CFL in the fibula [6, 10, 11, 15, 23, 24]. They showed that the ATFL superior fascicle (ATFLsf) is intraarticular whilst the ATFL inferior fascicle (ATFLif) is extra-articular and is connected with the CFL through arciform fibres. The CFL, ATFLif and their connections were described as a new anatomical structure: the lateral fibulotalocalcaneal ligament (LFTCL) complex [21]. In addition, medial connections have been described between the ATFL, CFL and PTFL [4]. These new LL anatomical concepts raise new perspectives on diagnosing and treating CAI (chronic ankle instability). Therefore, further investigation of these new concepts is needed using a 3D assessment.

This study aimed to assess the anatomical characteristics of the lateral ligaments and their relationships through a 3D view. To this end, the authors performed a cadaveric study using a light scanner to mark the footprints digitally. The hypothesis is that a 3D digital analysis can clarify the lateral ligaments connections and their relations, specifically regarding the attachments at the medial side of the lateral malleolus.

Materials and methods

The ethical committee of the University of Barcelona, with IRB number 00003099, approved this anatomical study. A total of 11 fresh-frozen ankle specimens were provided and dissected. The data were recorded for analysis, including the specimen's demographics (specimen identification, age, sex and side). Exclusion criteria included specimens with foot and ankle deformities, skin marks that suggested foot and ankle surgery or trauma, and lateral ligaments injury observed during dissection.

Each specimen was dissected in a standardised manner. An experienced anatomist in foot and ankle performed all dissections. After thawing the specimens by submersion in room temperature water, a plane-by-plane anatomical dissection was performed until the anterolateral ankle joint capsule was reached. At this point, the capsule was carefully dissected off the lateral ligaments to expose them. After the dissection, the ligaments' morphologic characteristics were analysed and recorded. The calcaneus, talus and fibula were separated in the next step, keeping the footprints and the ligament attachments. Subsequently, each bone was scanned by a white light structured scanner (HP 3D DAVID Scanner Pro S3). The scanner collected the bone surface information, morphology and texture with two cameras at a resolution of 0.06 mm, providing accurate measurements for anatomical studies [1]. The surface texture was captured to improve the identification of the studied areas. Each bone piece was set on a 3D automatic turntable to capture a 360° scan and was scanned in two orientations, with six scans per orientation. Finally, all the scans were aligned to create fused models using the HP DAVID software package and exported to a wavefront 3D object file (.obj) [1]. The 3D models were imported into Geomagic Studio 14.0 (3D Systems, Morrisville, NC, USA), a software that transforms 3D scanned data into highly accurate surface polygon models. Therefore, the 3D models were transformed into polygonal meshes that preserve all the surface information of the model to analyse the lateral ligament footprint's morphology and to calculate its surface areas (SA) with an accuracy of 0.01 mm2. The footprint areas of the talus, calcaneus and fibula were digitally selected by a single observer trained for this purpose, and the surface area was quantified in mm2. The distance from the centre of the CFL footprint to the nearest part of the posterior facet of the subtalar joint was also calculated.

Statistical analysis

Statistical analysis was performed using SPSS 23 (SPSS Inc., Chicago, IL, USA). The data were analysed descriptively using median and standard deviation, upper and lower limits of the 95% confidence interval (95% CI), and the minimum and maximum values were calculated. The Kolmogorov–Smirnov test was used for the normality of the data, and a one-way ANOVA test was used to test for significant differences by sex and laterality.

Results

Eleven units of each talus, fibula and calcaneus were dissected from eleven ankle specimens. It was five males and six females with an average age of 63 years old (range 41–88). The right ankle was dissected in five and the left ankle in six specimens.

The normality test showed that all the variables had a normal distribution (n.s) except the ATFLsf of the talus (n.s). The two one-way ANOVA showed no significant differences by sex and side (n.s). The ATFL was identified as a two-fascicled ligament, and the CFL as a single fascicle. The ATFLsf footprint was located only at the lateral side of the fibular malleolus, just inferior to the footprint of the anterior tibiofibular ligament. The footprint of the ATFLif was at the lateral and medial sides of the fibular malleolus. The connecting fibres between the ATFLif and CFL were present in all specimens (Fig. 1a). At the medial side of the fibula, the ATFLif, CFL and PTFL footprints were continuous in all cases (Fig. 1b). PTFL footprint on the malleolar fossa was inferior to the footprint of the posterior tibiofibular ligament (Fig. 1c). There was footprint continuity between the ATFLsf and PTFL at the medial side of the fibula in four cases (36%) (Fig. 2a). When the fibular malleolus was observed from the medial side, the footprints of the lateral ankle ligaments were found to be located surrounding the triangular medial articular surface of the fibular malleolus (Fig. 2b).

The talus had a separate footprint to each ATFL fascicle in nine specimens (81%) (Fig. 3a), whilst in two (19%), a continuous insertion was observed for both ATFL fascicles (Fig. 3b). The CFL insertion on the calcaneus was one single footprint in all cases. The average distance from the centre of the CFL footprint to the nearest part of the posterior facet of the subtalar joint was 19 (SD 3.2) mm (Fig. 4).

A complete list of the measurements obtained from the scanner is summarised in Table 1.

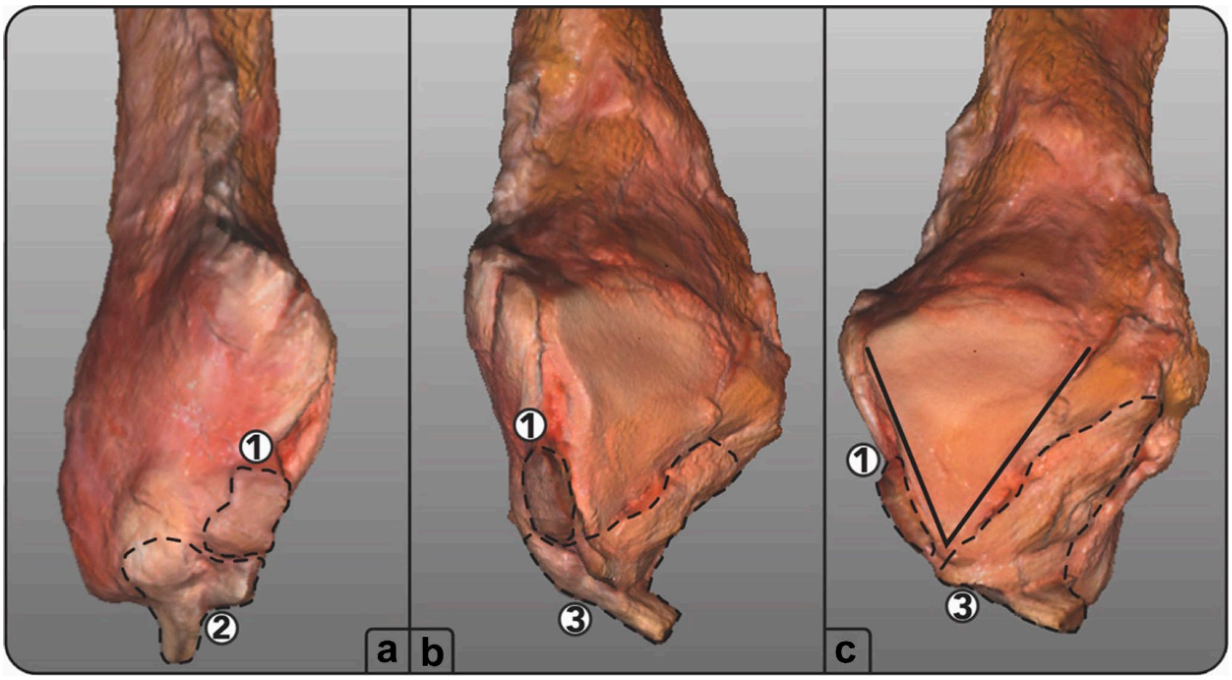

Fig. 1 Example of a 3D scan of the fibular malleolus. **a** Lateral and **b**, **c** medial view of a scanned fibula with the lateral ligament footprints: 1. ATFL superior fascicle 2. ATFL inferior fascicle and CFL. 3. Medial contiguous footprint of the PTFL, CFL and ATFL inferior fascicle

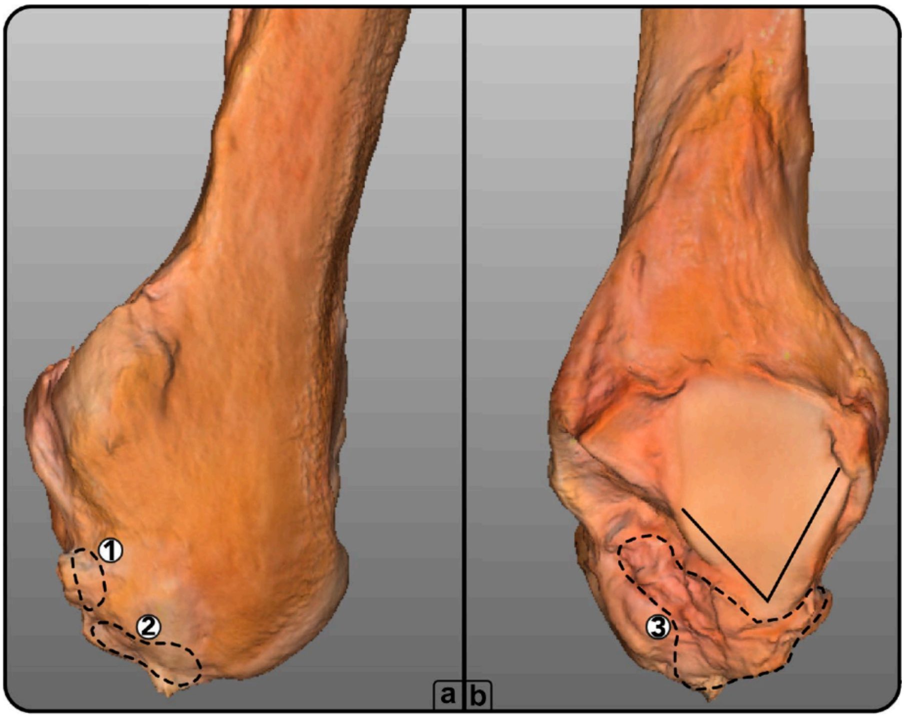

Fig. 2 **a** Lateral and **b** medial view of a scanned fibula with the lateral ligament footprints: 1. ATFL superior fascicle 2. ATFL inferior fascicle and CFL together with its connections. 3. Medial contiguous footprint of the PTFL, CFL and ATFL inferior fascicle with the ATFL superior fascicle

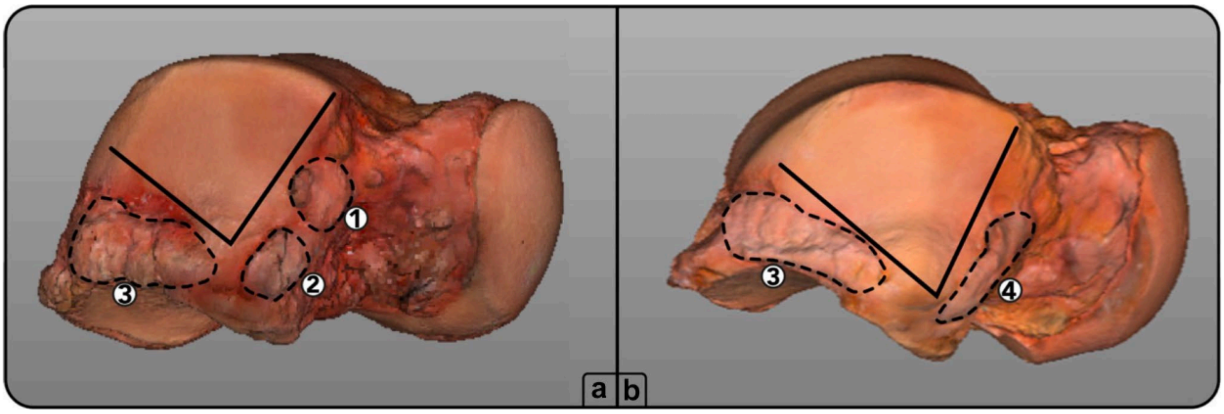

Fig. 3 **a**, **b** Lateral view of two scanned talus with the lateral ligament footprints: 1. ATFL superior fascicle 2. ATFL inferior fascicle. 3. PTFL, and **4.** a single ATFL footprint

Discussion

The most important finding of the present study was that the ATFLif, CFL and PTFL have a continuous fibular footprint at the medial side of the fibula. These findings suggest that the lateral ankle ligament complex is composed of two entities: the ATFLsf as one unit on its own, and second, a ligament complex formed by the ATFLif, CFL and PTFL.

This study is the first to analyse the lateral ligaments through a tridimensional view achieved by a digital marking of their footprints after a complete amputation of the bones. Earlier research focussed on the anatomy of the lateral ligaments using a 2D assessment [10, 22]. They found an independent fibular attachment of ATFL and CFL, contrasting the present study's findings. The method used for analysing the footprints of lateral ligaments has an essential role as it can directly influence the results. A 2D digital calliper evaluation may neglect the possible connections between

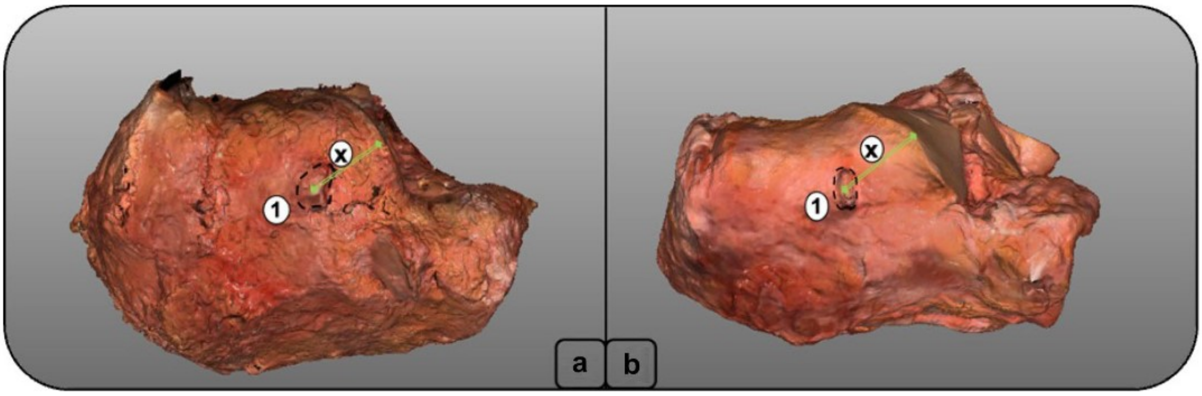

Fig. 4 **a**, **b** Lateral view of a scanned calcaneus showing a 1. single CFL insertion and X. the distance between the centre of the CFL footprint to the nearest part of the posterior facet of the subtalar joint

Table 1 Measurement data of the footprints in cm^2

	Fibula		Talus				Calcaneus
	ATFLsf	ATFL if + CFL + PTFL	ATFLsf	ATFLif	ATFLsf + if	PTFL	CFL
N	11	11	9	9	2	11	11
Mean	0.7	4.8	0.5	0.5	0.5	1.5	0.4
Median	0.6	4.5	0.5	0.4	0.4	1.4	0.4
Standard deviation	0.2	1.5	0.1	0.2	0.3	0.7	0.1

ATFLsf anterior talofibular ligament superior fascicle, *ATFLif* anterior talofibular ligament inferior fascicle, *CFL* calcaneofibular ligament, *PTFL* posterior talofibular ligament

the ligaments. Neuschwander et al. [15] performed the only study evaluating the footprints of the ATFL and CFL in a tridimensional view. They demonstrated that the CFL and ATFL have a single confluent footprint on the anterior border of the distal fibula. However, they omitted the PTFL, and the footprints were designed by hand. Beyond that, they did not resect the fibula to analyse the medial fibular footprints. The present study showed that the fibular ATFLif, CFL and PTFL footprints are continuous, mainly on the medial side of the inferior tip of the fibula. The ATFLsf foot was located at the anterolateral border of the fibula.

Besides the footprints, the morphology of the lateral ligaments is another topic that has been studied. Vega et al. [21] demonstrated the connection between ATFLif and CFL by arciform fibres describing the LFTCL complex. Cordier et al. [2] demonstrated the mechanical role of these fibres. Dalmau et al. [4] dissected 40 ankles and found connections between ATFLif, CFL and PTFL at the medial side of the fibula in all cases and between ATFLsf and PTFL in 42%. In agreement with that, the current study identified the ATFL as a two-fascicled ligament connecting fibres between ATFLif and CFL in all cases. All specimens demonstrated a continuous footprint of ATFLif, CFL and PTFL at the medial side of the fibula. Additionally, 36% of the cases showed continuity between ATFLsf and PTFL footprints. Regarding the CFL, Pereira et al. [17] presented, in an anatomical study, four distinct CFL morphological-oriented shapes. According to the finding of this study, these morphological variations were more related to the connecting fibres with the ATFLif than to CFL morphology variation. Concerning the CFL calcaneal footprint, it is well established that its footprint is located 13 mm posterior from the tip of the fibula [13]. Since the bones were evaluated separately, this distance was not measured. Therefore, the average distance from the centre of the CFL footprint to the nearest part of the subtalar joint's posterior facet was 19 mm.

The anatomical findings in the current study are similar to the latest anatomical descriptions of the lateral ankle ligament complex [2–4, 20, 21]. This research demonstrated that the ATFLif, CFL and PTFL have a continuous footprint on the medial side of the fibula. These data reinforce the concept of the lateral fibulotalocalcaneal ligament (LFTCL) complex described by Vega et al. [21], suggesting that the PTFL is also part of the LFTCL complex. The presented study has some clinical implications for diagnosing and treating patients with CAI. The findings of this study are useful when interpreting ligament aspects and injury patterns and can be used to improve imaging tools such as MRI.

The current data can also be used perioperatively, helping the surgeon to assess the ligament aspects and injury patterns. Regarding the treatment, these data may be used to guide the surgeon to repair and reconstruct the ligaments in an anatomical position. According to this research, it would make sense that the anchor for ATFLsf is placed at the anterolateral side of the fibula, whilst the anchor for ATFLif would be truly anatomical if placed at the inferior tip of the fibula (acknowledging placing it at the medial side of the malleolus carries other problems). Furthermore, the surgeon should know the normal origin and insertion to recognise a ligament avulsion. Finally, these anatomical findings allow us to improve the understanding of the pathomechanical concepts in patients with CAI. The different ligamentous structures of the LFTCL complex collaborate to keep the stability of the ankle. A lesion of a specific part of this structure may change the biomechanics of the other parts. A repair of the damaged part may allow restoring the normal anatomical properties. Further research is needed to identify which structures should be repaired or reconstructed in which patients.

This study has some limitations. A relatively small number of specimens were included. An evaluation of a more extensive series would improve the study's validity. Furthermore, ankles without laxity were used for this study to describe the normal anatomy of the lateral ligament complex, which may differ slightly in pathological cases. Finally, histological analysis of these footprints was not studied in this study and could undoubtedly be very useful to confirm that these ligaments form a single anatomical entity. The study strength is the 3D ligament footprint analysis after amputation of the bones, allowing complete visualisation of the footprints. Additionally, the ligament remnants were not touched, left intact on their footprint, and captured by the scanner. These features remove subjectivity and increase the reliability of this research.

Conclusion

The tridimensional analysis of the lateral ligaments of the ankle demonstrates that the ATFLif, CFL and PTFL have a continuous footprint at the medial side of the fibula in all specimens. These findings reinforce the concept of the lateral ankle ligament composed of two anatomical entities: the ATFLsf as one unit on its own and the LFTCL. It also demonstrates the PTFL as a part of the LFTCL, ATFLif and CFL. These findings should be considered when diagnosing and treating patients with CAI.

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Data availability The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no potential conflicts of interest with respect to the research, authorship and/or publication of this article. ICMJE forms for all authors are available online.

Ethical approval The ethical committee of the University of Barcelona, with IRB number 00003099, approved this anatomical study.

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ORIGINAL PAPER

All-inside arthroscopic repair of the anterior talofibular ligament: a case series

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Abstract

Introduction The all-inside arthroscopic repair of the anterior talofibular ligament (ATFL) is a technically challenging and still-recent procedure to treat chronic ankle instability (CAI). Favourable clinical outcomes have been shown from originator centers, but this is one of the first series from a non-originator centre. The purpose of the present study is to present the clinical and functional results of patients with CAI underwent arthroscopic all-inside ATFL repair.

Methods This is a series of cases of 18 consecutive patients who underwent the all-inside arthroscopic ATFL repair, for CAI, after the failure of conservative treatment performed for six months. The evaluation was made using the American Orthopaedic Foot and Ankle Score (AOFAS), visual analog pain scale (VAS), anterior drawer, and talar tilt tests.

Results All 18 patients were evaluated for a mean follow-up period of 12 months. There was an improvement in the AOFAS ($p < 0.001$), with the mean improving from 69.6 points to 98.1, standard deviation (SD) = 11.09, and in the mean VAS score ($p < 0.001$), from 5.0 to 0.5 points (SD = 0.78). All ankles were stable, as assessed by the anterior drawer test and talar tilt test. The only complication found was neurapraxia of the superficial fibular nerve in one patient (5%). All of the patients classified the treatment as good or excellent and returned to sports activities without limitations.

Conclusion Treatment of CAI by the all-inside arthroscopic ATFL repair was able to restore ankle stability and showed good clinical results and high satisfaction rates.

Keywords Joint instability · Ankle · Arthroscopy · Chronic ankle instability

Introduction

Injury of the lateral ligaments of the ankle joint is quite frequent and represents one of the most common sports injuries [1–3]. Approximately 20 to 40% of acute ankle ligament injuries may evolve to chronic lateral ankle instability (CLAI) and require a surgical approach [1–3]. The anatomical technique described by Broström and modified by Gould, which involves the repair of the ATFL and CFL and reinforcement with the extensor retinaculum, is considered

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the gold standard in the treatment of CLAI [3, 4]. The use of arthroscopy for direct inspection of the joint cavity in the evaluation of joint injuries associated with ankle ligament injury has also become fundamental in the treatment of these cases [5–10].

Recently, several cadaveric studies emerged that have implemented new biomechanical and anatomical concepts of the lateral ligament complex of the ankle, which have allowed a better understanding of the arthroscopic anatomy of the ankle [11, 12]. One of them was the mechanical role between the connecting fibers of the ATFL and CFL. The presence of this connection is the basis that may explain the fact that an isolated repair of the ATFL has excellent results in the treatment of CLAI when an injury of both the ATFL and CFL exists [11]. With the improvement of anatomical understanding and the evolution of arthroscopic devices, some authors have developed an all-inside arthroscopic ATFL repair using a knotless anchor [12, 13]. They demonstrated excellent clinical results with a low rate of complications, linked to a physiological restoration of ankle stability [12, 14]. Nevertheless, other authors criticized the use of anatomical techniques, which do not involve the extensor retinaculum or the CFL repair [7]. Furthermore, the all-inside arthroscopic ATFL repair is a technically challenging and still-recent procedure [9, 15] and the good results have been shown from originator centers, but this is one of the first series from a non-originator centre.

Thus, the purpose of this study was to compare the pre- and post-operative clinical and functional outcomes of a case series of patients with chronic lateral ankle instability who underwent all-inside arthroscopic ATFL repair.

Methods

The present study is a retrospective case series with prospectively and consecutively collected data on patients undergoing the all-inside arthroscopic ATFL repair. All patients underwent surgical treatment by a single foot and ankle surgeon (G.A.N.) with five years of experience in ankle arthroscopy and the follow-up was performed in a single institution. Clinical examination and functional evaluation were performed by a single trained examiner (R.M.C.) not involved in the surgery. The study was approved by the local ethics committee (CAAE: 45,339,221.0.0000.5128) and followed the Declaration of Helsinki and the Guidelines for Good Clinical Practice.

The sample included 18 consecutive patients (11 men and 7 women) with a mean age of 36 years old (ranging from 21 to 56), who were diagnosed with CLAI and were surgically treated with the all-inside arthroscopic ATFL repair technique [12, 13] between November 2018 and January 2020 at the Belo Horizonte Hospital. The mean follow-up time was 12 months (ranging from 9 to 18). Regarding the sports practiced, 12 patients were amateur competition athletes, five of them playing soccer, two tennis, two running, two volleyball, and one beach soccer. The other patients only practiced sports recreationally. There were no professional athletes.

The inclusion criteria were patients over 18 years of age diagnosed with chronic lateral ankle instability with a moderate or excellent ATFL remnant quality tissue. Diagnosis of chronic ligament instability were considered in patients with recurrent ankle sprain (more than three episodes in 1 year) associated with positive test for instability (anterior drawer test and talar tilt test) and magnetic resonance imaging (MRI) demonstrating ankle lateral ligament injury that did not improve with conservative treatment after 6 months [16]. The exclusion criteria were as follows: professional athletes, patients with CLAI with more than five years of evolution and with previous surgeries, in addition to associated lesions requiring additional procedures, such as osteochondral lesion of the talus, fibular tendinopathy, deltoid ligament injury, and cavovarus foot. Individuals with marked deformity, generalized ligament laxity, collagen diseases, neuromuscular diseases, and/or a body mass index (BMI) > 29 were also excluded.

Conservative treatment was performed using orthopaedic brace, analgesics, and functional rehabilitation. Instability tests were always performed comparatively with the injured and contralateral (healthy) sides, and were considered positive when there was an increase in the anterior excursion of the talus in the drawer test (groove sign) and varus opening in the talar tilt test in the injured side, compared to the contralateral side. The quality of the ligament-tissue remnant was evaluated arthroscopically and classified according Vega et al. description [17]. The moderate quality was a ligament with fibrotic tissue or synovitis, an initial good consistency, but fragile when it was reiteratively grasped. The excellent was a ligament with normal synovial tissue, sharply defined margins, and solid consistency when grasped [17].

Radiographic exams with ankle load were performed at anteroposterior incidences with 20° internal rotation and lateral rotation in all of the patients. In this study, no radiographs of the ankle under manual stress were performed. On MRI, patients had ATFL lesions, some of which were associated with a CFL lesion. The American Orthopaedic Foot and Ankle Score (AOFAS) [18] was used for the clinical and functional evaluation of the hindfoot and ankle, and the visual analog pain scale (VAS) [19] was used before surgery and at the last evaluation. Coughlin's classification [20] was used to assess patient satisfaction with treatment.

The range of motion (ROM) of the ankle was recorded at the last follow-up in a comparative way with the contralateral side using a digital inclinometer (Clinometer Smartphone Application™ Plaincode®, Munich, Bayern, Germany) [21], and the return to sports activities was also documented. All surgical complications were evaluated and recorded during follow-up.

Statistical analysis

The continuous variables were tested for the normality of their distribution through the Shapiro–Wilk test, and the categorical variables were measured by their proportion. The Wilcoxon signed test was used for the pre- and postoperative comparison of continuous variables. All statistical evaluations were performed by the R software, specifically by the Stats package, which are both open sources.

Surgical technique

1. The patient was placed under spinal anaesthesia and sedation, and was positioned supinely on the operating table. A pneumatic tourniquet was used on the thigh of the operated limb.
2. Anatomical points (joint line, anterior tibial tendon, superficial fibular nerve, and fibula) were demarcated for the preparation of traditional anterior arthroscopic portals of the ankle (anteromedial and anterolateral). No distraction was used.
3. The ankle joint was assessed with 4.0-mm optics to evaluate the presence of associated lesions.
4. The exploration of the lateral gutter was initiated, and debridement of the anterior inferior tibiofibular ligament (Basset ligament) was performed with a motorized 4.0-mm shaver. We used this ligament as an anatomical reference to locate the footprint of the ATFL in the fibula. In these cases, the ligament is usually detached from its fibular insertion and located in the lower region of the lateral gutter (Fig. 1). After identifying the ATFL lesion, the ligament was individualized and dissected from the lateral capsule.
5. The remaining ligament was looped and locked after the ends of the wires were passed through the loop through the anterolateral portal. This was done using an automatic suture passer (Scorpion, Arthrex®, Naples, FL, USA) positioned next to the fibula and mounted with 01 needle attached to a number 2 non-absorbable high-strength suture (FiberWire, Arthrex®, Naples, FL, USA) (Fig. 2).
6. In order to reproduce the native fibular insertion of the ATFL, the bone tunnel used to insert the anchor was created on the ATFL footprint. The drill was directed from anterior to posterior and parallel to the plantar region of the foot and lateral wall of the talus (Fig. 3a, b).
7. The sutures were connected to a SwiveLock 4.75-mm knotless anchor (Arthrex®, Naples, FL, USA) and inserted into the fibula, reinserting the ATFL. During anchor fixation, the suture was tensioned and the foot was kept in dorsiflexion and maximum eversion (Fig. 3c).
8. The reinsertion of the ligament and the tension achieved was evaluated with an arthroscopic probe (Fig. 3d).
9. The previous portals were sutured and dressed and the ankle was immobilized with an orthopedic boot.

Fig. 1 Arthroscopic view of the lateral gutter showing the fibular foot print of the ATFL (circle) and the remnant of the ATFL ligament (arrows)

Post-operative follow-up

For the first week, patients were instructed to remain unsupported and wear an orthopedic boot, keeping the ankle in a neutral position. On the third day after surgery, the first dressing change was performed, followed by daily changes. A partial support with an orthopedic boot and the aid of crutches was prescribed beginning the second week. From the fourth week, the patients were instructed to replace the boot with a semi-rigid orthosis and begin a physical therapy rehabilitation program. In the sixth week, immobilization was removed and the physical therapy rehabilitation program was continued. The return to non-contact sports was allowed between six and eight weeks after surgery, while contact sports were allowed after three months of surgery.

Results

A total of 18 patients (18 ankles) were submitted to surgical treatment, most of them male (61%), with predominance of the left side (55%) and a mean age of 36 years (standard deviation [SD] = 8.75). Isolated ATFL lesions on MRI were found in 13 patients (72%) and the joint lesion of the ATFL and CFL in five (28%).

The clinical evaluation revealed a VAS result of preoperative pain with a mean of 5.00 (SD = 1.37) and a

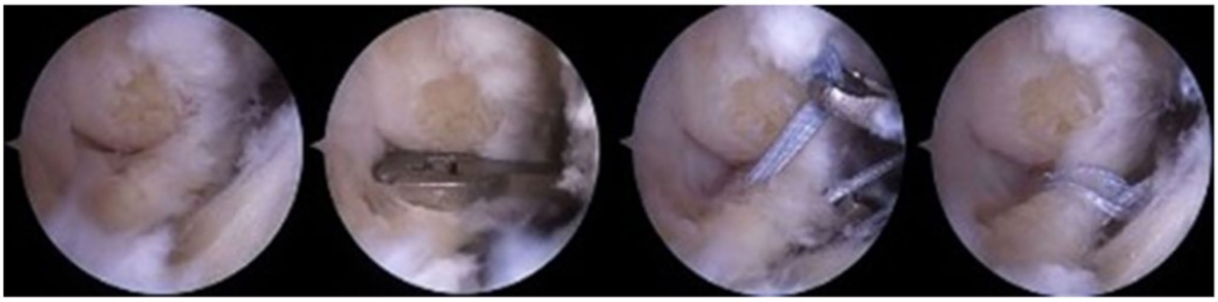

Fig. 2 An automatic suture passer was used to grasp the ATFL

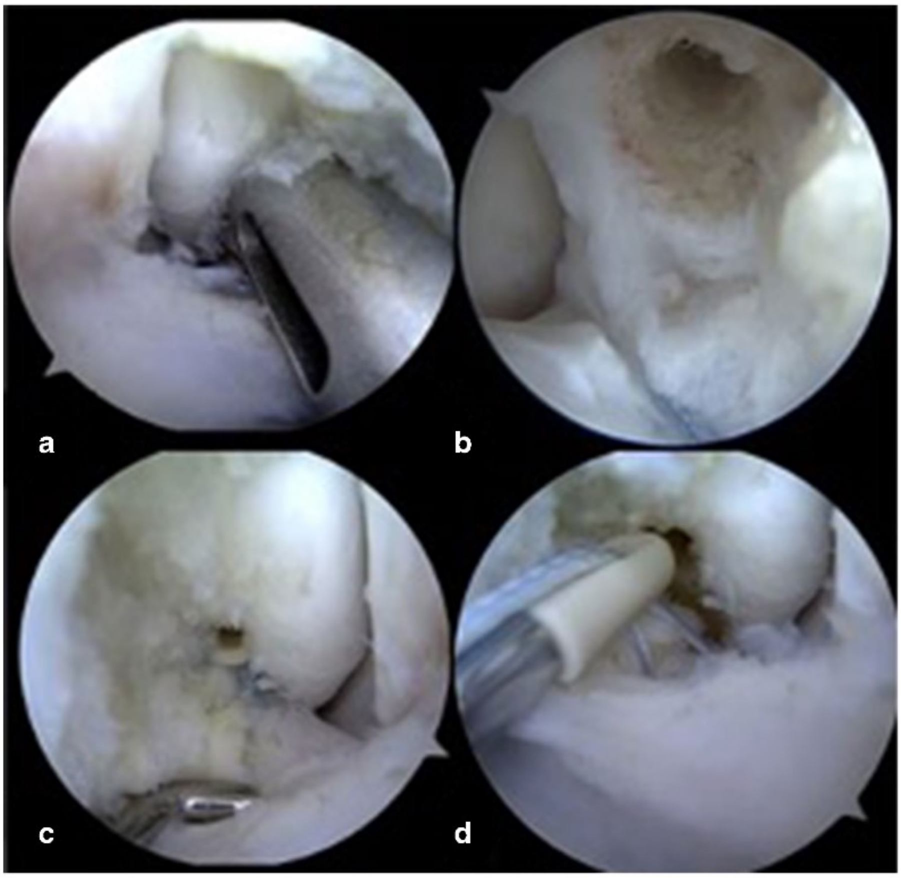

Fig. 3 **a** The fibular tunnel was drilled. **b** View of the bone tunnel. **c** The knotless anchor was inserted reinserting the ligament. **d** The ligament reinsertion was tested using an arthroscopic probe

post-operative mean of 0.55 (SD = 0.78), with a statistically significant difference of 3.63 points ($p < 0.001$). The pre-operative mean of AOFAS was 69.67 (SD = 11.09) points, and the post-operative mean was 98.17 (SD = 2.45) points, representing an increase of 28.50 points, which was also statistically significant ($p < 0.001$). The ROM assessment of the ankle showed a difference of 5° in five patients and 10° in one patient. All of the ankles were stable, with normal anterior drawer and talar tilt results.

The degree of satisfaction with the procedure was high; 67% of the patients classified the result as excellent and 33% as good. No patient classified the result as poor or very poor. All patients returned to their daily and sports activities without limitations.

Regarding complications, one patient (5%) reported paresthesia in the region of the superficial fibular nerve, which improved spontaneously. There was no recurrence of instability, superficial or deep infection, surgical wound dehiscence, or need for re-operation in any patient.

Discussion

In the present study, the surgical treatment of CLAI, performed through the all-inside arthroscopic ATFL repair technique, presented good clinical and functional results. All of the patients presented restoration of ankle stability and were able to return to sports activities. These findings were accompanied by a low complication rate (5%) represented by one patient with transient neuropraxia of the superficial fibular nerve.

As we know, the open lateral ligament repair as originally described by Broström is considered the gold standard procedure to surgically treat CLAI [2]. Even so, since the importance of chronic ankle instability-associated injury treatment was demonstrated, ankle arthroscopy has become essential [5]. Meanwhile, focused in reducing surgical aggression, recovery time, and post-operative pain, ankle arthroscopic techniques have evolved significantly in recent years. They have the advantage of a minimally invasive approach and the added benefit of arthroscopically treating any concomitant intra-articular pathology, in addition to ankle instability [9, 12]. A systematic review published by Brown et al. demonstrated favourable clinical outcomes in the short term of arthroscopic lateral ankle ligament repair [22]. Furthermore, as shown in this study, we can arthroscopically reproduce the same anatomical repair performed by an open approach, obtaining similar results with the advantage of being a minimally invasive procedure.

The results obtained from this non-originator all-inside arthroscopic repair of the ATFL case series supports the safety and success rate of this anatomical and purely arthroscopic procedure to treat CLAI described previously. Vega et al. [12] demonstrated a series of cases consisting of 16 patients with CLAI treated by the all-inside arthroscopic ATFL repair technique, obtaining an increase in the AOFAS from 67 to 97 points without any case of recurrence. Guelfi et al. [23] also evaluated 25 patients with CLAI with a mean follow-up time of 34 months and achieved restoration of stability in all of the cases with an improvement in AOFAS from 60 to 94 points and VAS reduction from 6 to 0.9 points.

Most of the cases studied in this series presented isolated lesions of the ATFL, while only one-third of the cases presented combined lesions of the ATFL with the CFL. Although some authors criticized the use of anatomical techniques, which do not involve the use of the extensor retinaculum and CFL [7], concomitant lesions of the ATFL and CFL may not be a contraindication to perform this technique. Maffulli et al. presented a long-term follow-up of isolated anatomic repair of the ATFL in 42 physically active patients with mechanical ankle instability and concluded that this approach is safe and effective and allows safe return to preinjury sport activity [24]. Recent anatomical studies [4, 11, 25] demonstrated that the CFL is connected to the ATFL, transmitting tension between both ligaments. Thus, it was considered that arthroscopic repair of the ATFL also implies the tensioning of the CFL in cases where it was injured, without impairing the final stability of the procedure.

Some degree of limitation in ankle ROM is expected after ATFL repair. It has been found that a more significant loss (from 10°) of ROM after ligament repair may compromise the functional outcome and an early return to sports activities [8, 12]. It was also noted that this stiffness is more present in percutaneous ligament repair techniques assisted by arthroscopy because they involve the capsule, retinaculum, and sural fascia in the same suture, generating too much fibrosis in the lateral ankle groove [9]. In the present study, only one case was identified with a 10° limitation, without impairing the satisfaction of this patient.

One patient (5%) presented with neuropraxia of the superficial fibular nerve, which evolved with spontaneous resolution. Similar rates of this complication have also been reported in other case series that evaluated this arthroscopic ATFL repair [12, 23]. It is important to highlight that the rate of neurological injury in this series was lower than that found in other studies of patients treated by the AB technique. Pellegrini et al. [26] observed transient neurapraxia of the superficial fibular nerve in 15% of a series of cases, while Acevedo et al. [7] and Corte-Real et al. [27] reported a rate of 6.8% and 10.7%, respectively. The authors believe that the arthroscopic technique used in this study presented a lower risk of incarceration of the superficial fibular nerve because the suture and reinsertion of the ATFL were performed only within the joint by direct arthroscopic vision, disregarding the percutaneous step, in which the sutures are externalized and then collected subcutaneously.

Although it is a technically more complex procedure that requires experience of the surgeon, ATFL all-inside arthroscopic anatomical repair was described as a safe and reproducible procedure [14]. The findings of this study reinforce this impression, since this series was carried out in a non-originator center, which included the surgeon's learning curve with this technique, being able to replicate the published data. However, in order to be successful, it is essential that the surgeon has expertise with ankle arthroscopy and familiarity with the anatomy of the lateral ligament complex.

It is important to emphasize that to restore ankle stability through a direct and isolated repair, the quality of the remaining ligament must be good enough to be grasped, tensioned, and reinserted into the native footprint [28]. The authors prefer to perform an augmentation in patients with poor quality of the ATFL remnant ligament. In addition, those large patients with a BMI > 29 and high-demand professional athletes who need for a quick recovery and return to sports activities are also indicated for an augmentation.

Major strengths of the present study are that a single experienced surgeon performed all interventions, while an independent assessor performed all post-operative investigations. To the best of our knowledge this is one of the first series of the all-inside arthroscopic repair of the anterior talofibular ligament (ATFL) from a non-originator centre. Another advantage is that we excluded patients with associated injuries that required additional procedures and would modify the post-operative period.

There are several limitations of this study. Firstly, pre-operative and post-operative instability findings could not be assessed with the quantitative values. Second is the absence of a control group treated by an open approach and a short mean follow-up time to evaluate some complications. Other limitations are that the ankle ROM was not evaluated pre-operatively and AOFAS is not a validated scale for results to assess ankle instability and, consequently, certain clinical features could have been ignored [29]. Although there are other questionnaires for assessing ankle instability, they have not been validated in the official language of the patients of this study. Finally, the sample was not homogeneous, as patients with isolated ATFL lesion and combined ATFL and CFL lesion were included in the same group.

Conclusion

Surgical treatment of chronic lateral ankle ligament injury by the all-inside arthroscopic ATFL repair technique was able to restore stability, achieved good clinical results, and was associated with a low complication rate. Nevertheless, longer-term follow-up and further comparative trials studies are necessary to confirm the benefits of this procedure.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Gustavo Araujo Nunes, Gabriel Ferraz Ferreira, Rafael Medeiros Caetano, Tania Szejnfeld Mann, and Matteo Guelfi. The first draft of the manuscript was written by Gustavo Araujo Nunes, Gabriel Ferraz Ferreira, and Rafael Medeiros Caetano, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Availability of data and materials The datasets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The study was approved by the Bioethics Committee of Medical Institution on the Plataforma Brasil, CAAE number: 45339221.0.0000.5128. ICMJE forms for all authors are available online.

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication The authors affirm that human research participants provided informed consent for publication of the images in Figs. 1, 2, and 3. The participant has consented to the submission of this case series to the journal.

Conflict of interest The authors declare no competing interests.

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Highlights - The first case series from nonoriginator center of this procedure

- Homogeneous case series operated and followed by the same surgeon
- Important clinical and functional improvement with a low rate of complications
- High rate of return to sports after the procedure
- Restoration of ankle stability in all cases, including those with associated CFL injury

Article

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Arthroscopic-Assisted Versus All-Arthroscopic Ankle Stabilization Technique

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Abstract

Background: Both the percutaneous technique with arthroscopic assistance, also known as arthroscopic Broström (AB), and the arthroscopic all-inside ligament repair (AI) are widely used to treat chronic lateral ankle instability. The aim of this study was to compare the clinical outcomes of these 2 arthroscopic stabilizing techniques.
Methods: Thirty-nine consecutive patients were arthroscopically treated for chronic ankle instability by 2 different surgeons. The AB group comprised 20 patients with a mean age of 30.2 (range, 18-42) years and a mean follow-up of 19.6 (range, 12-28) months. The AI group comprised 19 patients with a mean age of 30.9 (range, 18-46) years and mean follow-up of 20.7 (range, 13-32) months. Functional outcomes using the American Orthopaedic Foot & Ankle Society (AOFAS) hindfoot score and visual analog pain scale (VAS) were assessed pre- and postoperatively. Range of motion (ROM) and complications were recorded.
Results: In both groups the AOFAS and VAS scores significantly improved compared with preoperative values ($P < .001$) with no difference ($P > .1$) between groups. In the AB group the mean AOFAS score improved from 67 (range, 44-87) to 92 (range, 76-100) and the mean VAS score from 6.4 (range, 3-10) to 1.2 (range, 0-3). In the AI group the mean AOFAS score changed from 60 (range, 32-87) to 93 (range, 76-100) and the mean VAS score from 6.1 (range, 4-10) to 0.8 (range, 0-3). At the final follow-up 8 complications (40%) were recorded in the AB group. In the AI group 1 complication (5.3%) was observed ($P < .05$).
Conclusion: Both the AB and AI techniques are suitable surgical options to treat chronic ankle instability providing excellent clinical results. However, the AB had a higher overall complication rate than the AI group, particularly involving a painful restriction of ankle plantarflexion and neuritis of the superficial peroneal nerve.
Level of Evidence: Level III, retrospective comparative study.

Keywords: ankle arthroscopy, ankle instability, ligament repair, arthroscopic Broström, all-inside repair, comparative study

Introduction

Ankle sprains are one of the most common orthopedic injuries, with the lateral ligament complex being involved in 85% of cases.[14,16] Ankle sprains can lead to instability in 10% to 40% of patients, and some of them will require surgical intervention to restore ankle stability. [6,13]

In the past, anatomical open lateral ligament repair as originally described by Broström was considered the gold standard procedure to surgically treat ankle stability.[5] However, the potential for addressing both the instability and any intra-articular associated pathology arthroscopically has deemed ankle arthroscopy as better positioned to be the technique of choice when treating ankle instability.

Hawkins[19] described the first arthroscopic ankle stabilization technique in 1987, although subsequent complaints arose due to the prominent staple used in that technique. Since then, the technical aspects of ankle arthroscopy and

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instruments have significantly evolved, providing much better results in the treatment of ankle instability.

As has been the case in open surgery, a number of arthroscopic techniques have been proposed to restore ankle stability. These can be broadly classified into arthroscopic-assisted and all-arthroscopic techniques. Arthroscopic-assisted techniques combine arthroscopic procedures with a percutaneous[1] or mini-open approach,[19] whereas the all-arthroscopic techniques[32] involve a fully arthroscopic procedure. All-arthroscopic techniques can be further subdivided into ligament repair and ligament reconstruction or ligamentoplasty. The emergence of publications reporting excellent clinical results has helped to popularize both arthroscopic-assisted and all-arthroscopic ligament repairs.[8,23,25,32]

The percutaneous technique with arthroscopic assistance has also been termed arthroscopic Broström (AB). The procedure entails arthroscopic insertion of anchors into the fibula and a percutaneous step to stitch the lateral ligament and the inferior extensor retinaculum (IER). The technique yields excellent clinical results despite a high rate of reported complications (5.3%-29%) due to neurological entrapment or prominent implants.[8,18,22] The all-arthroscopic ligament repair technique, popularized as the arthroscopic all-inside ligament repair (AI), is an anatomical repair of the lateral ligaments under direct arthroscopic visualization with the use of anchors.[32,33] Excellent clinical results have been reported with a low rate of complications, mostly minor ones.[17,27,32]

The purpose of this study was to compare the clinical outcomes of 2 arthroscopic stabilizing techniques used for chronic lateral ankle instability: the percutaneous technique with arthroscopic assistance and the all-arthroscopic ligament repair.

Methods

From February 2016 to June 2018, 39 consecutive patients were arthroscopically treated for chronic ankle instability, after being assessed due to limitations in their daily activities. Surgeries were performed by 2 surgeons trained in foot and ankle arthroscopy, each with more than 3 years of experience and more than 30 cases performed of the described techniques.

Patients were included in 2 groups: the first one underwent the percutaneous technique with arthroscopic assistance (AB), and the second the arthroscopic all-inside ligament repair (AI). Each technique was always performed by the same surgeon, without crossing over. The AB group comprised 20 patients (8 males and 12 females) with a mean age of 30.2 (range, 18-42) years. The right ankle was affected in 13 cases. The mean follow-up was 19.6 (range, 12-28) months. The AI group comprised 19 patients (9 males and 10 females) with a mean age of 30.9 (range, 18-46) years. The right ankle was affected in 9 cases. The mean follow-up was 20.7 (range, 13-32) months.

Inclusion criteria included chronic ankle instability with a minimum duration of symptoms of 6 months. Clinical findings consisted of anterolateral pain, recurrent ankle sprains, or a feeling of the ankle giving way along with a positive anterior drawer test. All patients underwent a 3- to 6-month course of nonoperative treatment (anti-inflammatory therapy, rest, and physiotherapy) without improving.

Patients with previous foot and ankle surgery, malalignment, or end-stage tibiotalar joint osteoarthritis were excluded. Exclusion criteria consisted of the presence of a talar osteochondral lesion, peroneal tendon pathology, or deltoid ligament tear. Cases of generalized ligamentous laxity and neuromuscular diseases were also discarded from the study. The observation of a calcaneofibular ligament (CFL) tear in addition to the anterior talofibular ligament (ATFL) tear was not an exclusion criterion.

Full weightbearing radiographs and magnetic resonance imaging (MRI) were obtained in all cases to obtain a complete imaging study. No stress radiographs were requested.

Functional outcomes using the American Orthopaedic Foot & Ankle Society (AOFAS) hindfoot score and visual analog pain scale (VAS) were assessed preoperatively and at the latest follow-up (minimum of 1 year after the procedure) by a third surgeon not involved in the surgeries. Preoperative and latest follow-up ankle anterior drawer test scores, range of motion (ROM), and complications were recorded. At the latest follow-up, the anterior drawer test score and ROM were compared with the healthy contralateral side. Ankle ROM was measured by a goniometer and a postoperative deficit >10 degrees with discomfort or pain was classified as a minor complication.

The study was approved by the ethics committee of our institution.

Surgical Technique

The instruments required for the arthroscopic procedure included a 4.0-mm 30-degree scope, 3.5-mm arthroscopic motorized shaver, and burr plus standard arthroscopic instruments. Patients were positioned supine under spinal anesthesia with a thigh tourniquet. Cutaneous landmarks over the anterior aspect of the ankle were highlighted.

An ankle dorsiflexion arthroscopic and no-distraction technique was performed that allowed access to the lateral gutter.[9,11] Standard anteromedial and anterolateral portals were established. The anteromedial portal was mainly used as a visualization portal for the arthroscope, whereas instruments were introduced through the anterolateral portal. A full arthroscopic examination was performed, and when present, scar tissue or synovitis was debrided before proceeding to the stabilizing technique.

Percutaneous Technique With Arthroscopic Assistance

The footprint of the remaining ligament on the fibula was debrided with an arthroscopic shaver to create a rough area that would promote healing.

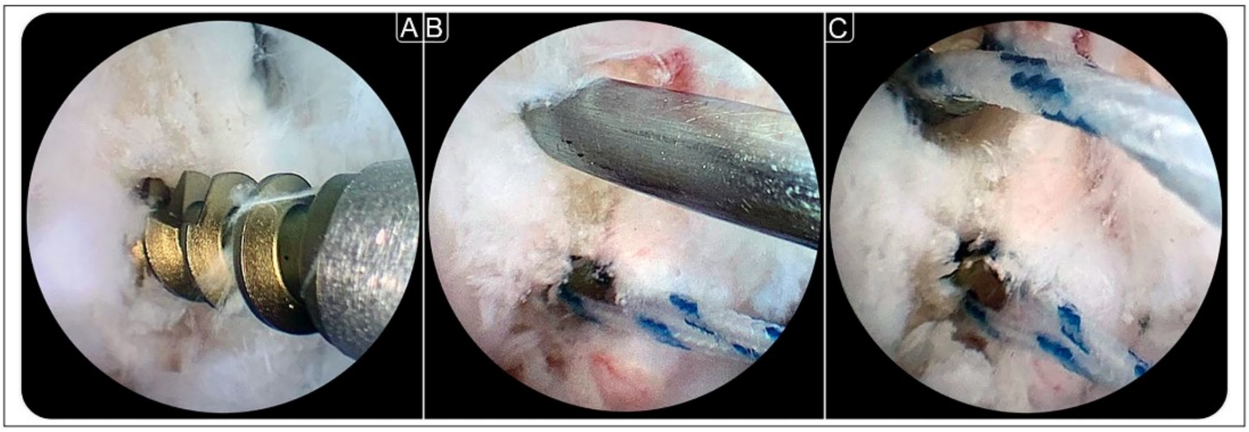

Figure 1. Arthroscopic-assisted placement of 2 suture anchors in the lateral malleolus during arthroscopic Broström. Anchors are placed at approximately 0.5 cm from each other.

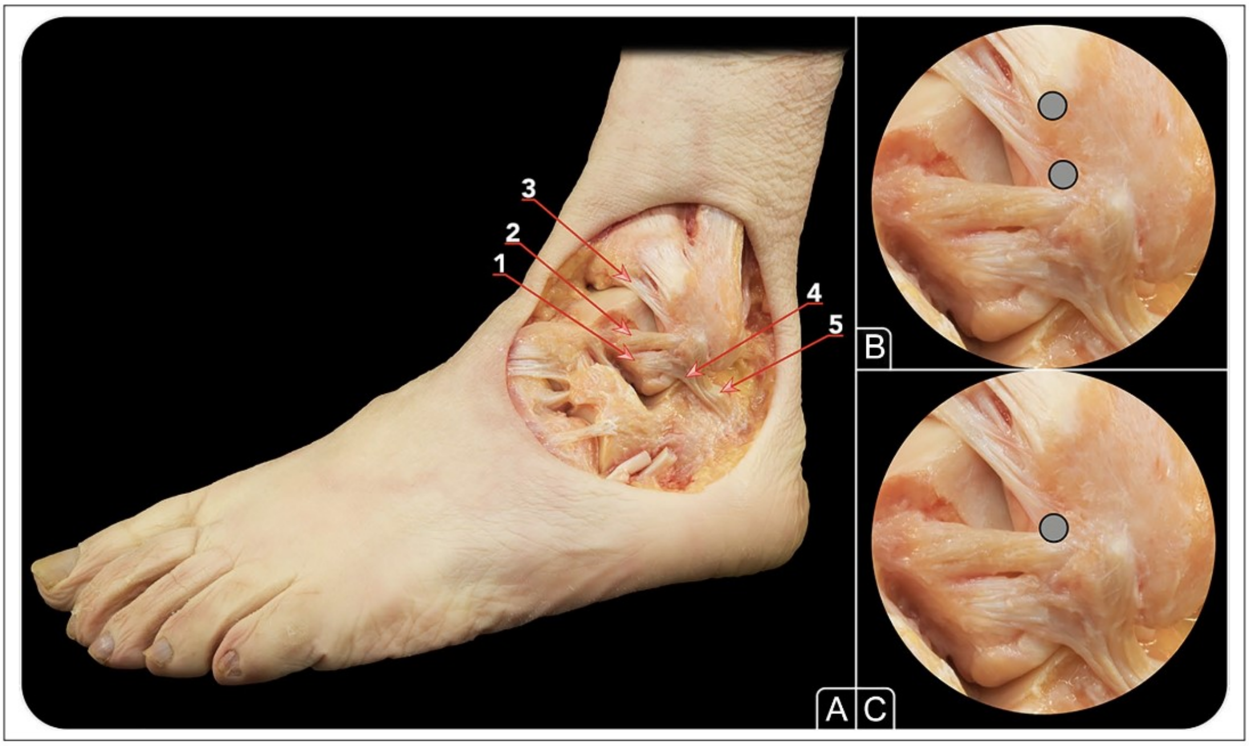

Figure 2. Anterolateral view of an anatomical dissection depicting the (A) anatomy of the lateral ankle ligaments and the position of the anchors for the (B) arthroscopic Broström and (C) all-inside technique. 1, anterior talofibular ligament's (ATFL's) inferior fascicle; 2, ATFL's superior fascicle; 3, distal fascicle of anterior tibiofibular ligament; 4, fibers of the lateral fibulotalocalcaneal ligament complex; 5, calcaneofibular ligament.

Two bone anchors (3.5 × 10–mm CorkScrew; Arthrex, Naples, FL) were introduced through the anterolateral portal and placed 1 and 1.5 cm proximal to the tip of the fibula (Figures 1 and 2).[31] Sutures were pulled out from the anterolateral portal. Next, with the ankle in neutral position, sutures coming from the distal anchor were passed inside out with the use of a suture passer (SutureLasso; Arthrex). The suture passer loaded with one of the sutures was directed first proximally to the peroneal tendons, at about 1.5 cm distal to the apex of the fibula; then a second suture was passed 1 cm proximal to the first suture. Next, sutures from the second anchor were passed with the suture passer at about 1 cm medial to the last suture, and the same with the other suture at 1 cm medial from it (Figure 3). Sutures were intended to

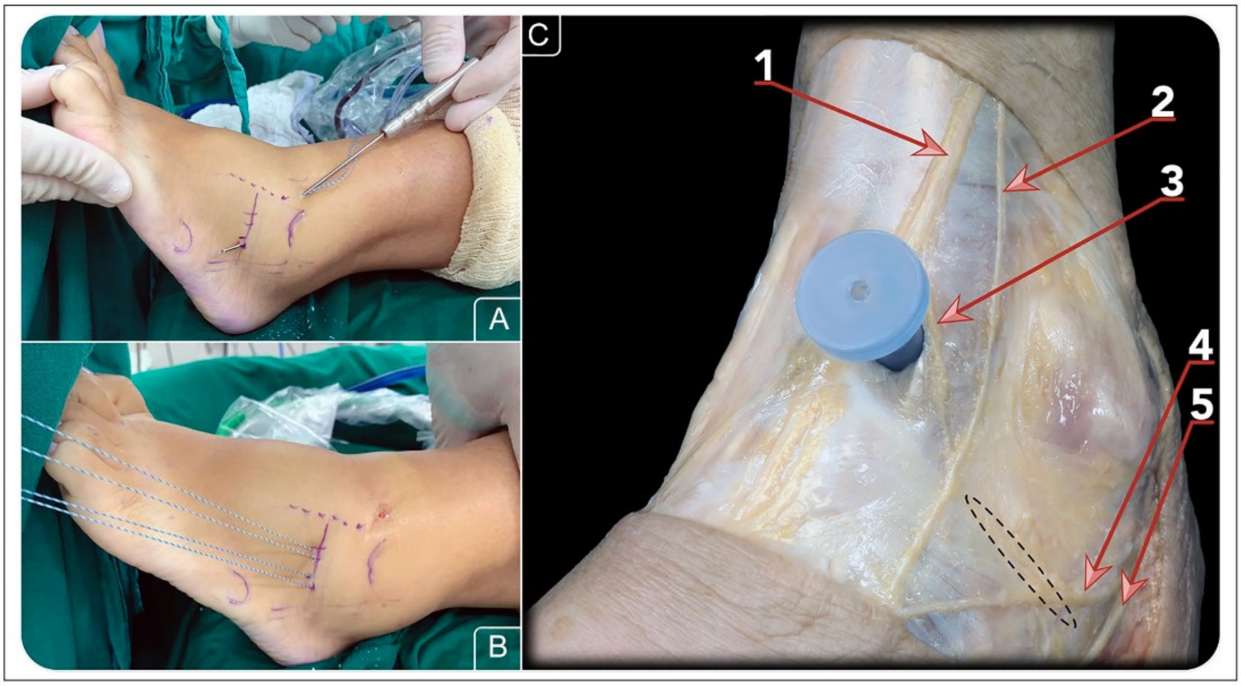

Figure 3. (A,B) Percutaneous suture passing and (C) anatomy of relevant nerves in the arthroscopic Broström. (C) A cannula has been inserted through the anterolateral portal. 1, medial dorsal cutaneous nerve (branch of superficial peroneal nerve); 2, intermediate dorsal cutaneous nerve (branch of superficial peroneal nerve); 3, communicating branch; 4, communicating branch; 5, sural nerve. The dotted area represents the location of the suture.

penetrate the IER while avoiding the superficial peroneal nerve. Two small incisions were made between sutures in order to subcutaneously retrieve them. Next, with the ankle in neutral dorsiflexion and slight eversion, a sliding knot was made with the sutures in every anchor. The stitch was aimed to grasp the ligament structures, the capsule joint, and the IER. Finally, sutures were cut and the incisions closed. A removable walking booth was applied.

Arthroscopic All-Inside Ligament Repair

In addition to the standard portals, an accessory anterolateral portal was located about 1 to 1.5 cm proximal to the fibular tip and just anterior to it. The fibular ligament footprint was debrided with an arthroscopic shaver to facilitate the ligament healing. A suture passer (Microsuture lasso 70 degrees curved; Arthrex) was introduced through the anterolateral portal to grasp the ATFL remnant from lateral to medial. Next, the nitinol loop was inserted into the ankle joint and pulled out through the accessory portal. The nitinol was then replaced by a doubled high-resistance suture (Fiberwire No. 0; Arthrex). The limbs of the suture located in the accessory portal were passed through the anterolateral portal. Next, one limb of the sutures was passed through the loop suture, creating a lasso loop. By pulling both suture limbs, the lasso loop was introduced into the joint and the ATFL remnant was grasped. To reattach the ATFL onto its native insertion, a bone tunnel for the knotless anchor was drilled just distal to the fibular attachment of the anterior tibiofibular ligament distal fascicle (Figure 2C). Next, the knotless anchor (Pushlock 2.9 × 15.5 mm; Arthrex) was loaded with sutures and introduced into the fibular tunnel by impaction while the ankle was held in dorsiflexion and eversion (Figure 4). Finally, sutures were cut with arthroscopic scissors and the incisions were closed. A removable walking boot was applied.

Postoperative Protocol

The same postoperative protocol was utilized in both groups. The removable walking boot was kept on at all times for the first 3 to 4 weeks. Partial weightbearing as tolerated with the aid of crutches was recommended from the day following surgery. Formal physiotherapy was initiated after the walking boot was removed. Progressive strengthening and exercises to increase ROM of the ankle were advised. Return to noncontact sports (eg, swimming and cycling) was allowed 2 months postoperatively, and return to any sports without restrictions was allowed 3 months postoperatively depending on muscle conditioning.

Statistical Analysis

Statistical analysis was performed using SPSS 23 (IBM Corp, Armonk, NY). Descriptive results were presented as median, mean, and range. Several tests were used to

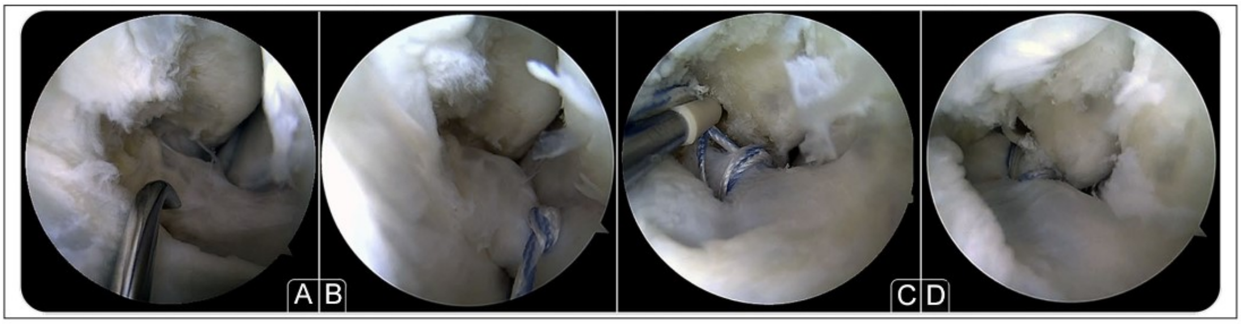

Figure 4. Arthroscopic all-inside anterior talofibular ligament (ATFL) repair. With the help of a (A) suture passer the ATFL is grasped with a (B) high-resistance suture. With a (C) knotless anchor the ligament is reattached onto its (D) native footprint.

Table 1. Characteristics of Arthroscopic Broström and All-Inside Ligament Repair Groups.

	Arthroscopic Broström group	All-inside repair group	*P* value
No. of patients	20	19	
Sex (male/female)	8/12	9/10	
Side (right/left)	13/7	9/10	
Mean age, y (range)	30.2 (18-42)	30.9 (18-46)	<.001
Mean follow-up, mo (range)	19.6 (12-28)	20.7 (13-32)	<.001

evaluate the difference between both surgical techniques. For qualitative variables, Pearson's chi-square and Fisher statistical test were used with continuity correction when necessary. For quantitative variables, the Mann-Whitney *U* test for independent samples was used, since the null hypothesis of data normality by the Kolmogorov-Smirnov test was rejected. Pre- and postoperative VAS and AOFAS results were also evaluated with the Wilcoxon signed-rank tests. P values $<.05$ were considered statistically significant.

Results

The 2 groups were homogenous, and no significant difference was noted in mean age and follow-up (Table 1).

In both groups the AOFAS and VAS scores significantly improved compared with preoperative values ($P < .001$) (Table 2): in the AB group the mean AOFAS score improved from 67 (range, 44-87) to 92 (range, 76-100) and the mean VAS score from 6.4 (range, 3-10) to 1.2 (range, 0-3); in the AI group the mean AOFAS score changed from 60 (range, 32-87) to 93 (range, 76-100) and the mean VAS score from 6.1 (range, 4-10) to 0.8 (range, 0-3). With regard to the AOFAS and VAS improvement, there was no difference ($P > .1$) between groups.

At the final follow-up, 8 complications (40%) were recorded in the AB group (Table 3). Four patients (20%) presented a deficit in ankle plantarflexion >10 degrees compared with the contralateral side, complaining of mild discomfort or pain when plantarflexing the ankle, and it was considered a minor complication. A transient neuritis of the superficial peroneal nerve was experienced in 3 patients (15%). In 1 case (5%) the prominent suture knots required anchor removal 4 months after surgery. Regarding the AI group, only 1 complication (5.3%) involving painful ankle plantarflexion deficit >10 degrees was observed and was considered a minor complication. No cases of neuritis, anchor prominence, or other complications were noted. The differences in complication rates between groups were statistically significant ($P < .05$).

At the latest follow-up, all patients reported subjective improvement in their ankle stability. On clinical examination, the anterior drawer test and the talar tilt test were negative in all patients. To date, no patients required ligament revision surgery. All patients returned to daily and recreational activities without limitations. One patient in the AB group had an ankle sprain after returning to sport activities that was treated conservatively.

Discussion

The most important contribution of this study is that both AB and AI demonstrated similarly excellent clinical results according to AOFAS and VAS scores. However, AB had a higher potential risk of complications.

Arthroscopic techniques to treat ankle instability have significantly evolved in the recent years. While attracting interest from foot and ankle surgeons both the AB and the AI have gained further popularity. They present with the advantage of a minimally invasive approach and the added benefit to arthroscopically treat any concomitant intra-articular pathology besides that of ankle instability. Intra-articular pathology is frequently observed in association with ankle instability, and its treatment at the time of surgery is essential for an optimal result.[3,20,21,29] We believe the potential for addressing both the instability and any associated pathology places ankle arthroscopy as the technique of choice in the presence of ankle instability.[3,7,15,20,21]

Table 2. Clinical Outcomes of Arthroscopic Broström and All-Inside Ligament Repair Groups.

	Scale	Preoperative (range)	Postoperative (range)	*P* value
Arthroscopic Broström group	VAS	6.4 (3-10)	1.2 (0-3)	<.001
	AOFAS	67 (44-87)	92 (76-100)	<.001
All-inside repair group	VAS	6.1 (4-10)	0.8 (0-3)	<.001
	AOFAS	60 (32-87)	93 (76-100)	<.001

Abbreviations: AOFAS, American Orthopaedic Foot & Ankle Society; VAS, visual analog pain scale.

Table 3. Complications of Arthroscopic Broström and All-Inside Ligament Repair Groups.

Complication	Arthroscopic Broström group (n = 20) (%)	All-inside repair group (n = 19) (%)	*P* value
ROM limitation	4 (20)	1 (5.3)	
Neuritis of SPN	3 (15)	0	
Prominence of suture	1 (5)	0	
Total complications	8 (40)	1 (5.3)	.012

Abbreviations: ROM, range of motion; SPN, superficial peroneal nerve.

Previous studies on AB and AI demonstrated excellent clinical results and a low rate of recurrence of instability of the ankle.[2,8,18,25,27,32] These findings were confirmed in the current study with a statistically significant improvement in clinical scores (AOFAS and VAS) ($P < .001$). When the 2 techniques were compared, no differences were observed in clinical results ($P > .1$). At the latest follow-up, no recurrence of instability was reported in any group.

The main difference observed in the literature between both techniques is in complication rates. Higher complication rates have been reported in the AB technique (5.3%-29%).[18] The 2 most frequently reported complications are neuritis of the superficial peroneal nerve and pain or discomfort due to a prominent anchor or suture knot.[18] This reported higher rate of complications in the AB technique was also confirmed in the current study (40%). Efforts were made to describe a "risk-free" zone for the AB technique,[2] although it is our opinion that nerve complications can be explained due to the percutaneous passage of the suture along the anterolateral aspect of the ankle. In addition, the affected superficial peroneal nerve is known to have multiple anatomical variants plus a mobile path that varies depending on ankle dorsiflexion.[12,28] Anatomical variations in the nerve distribution pose higher risk of injury by the subcutaneous suture passing.[28] Moreover, the nerve moves approximately 2.4 mm laterally when the ankle is dorsiflexed when compared with a plantarflexed and inverted position.[23] In contrast to the AB, the AI is a fully arthroscopic procedure in which the ligament is grasped intra-articularly under direct arthroscopic vision, obviating any risk of subcutaneous nerve entrapment.[17]

As for the postoperative stiffness, it is accepted that a mild deficit in ROM is expected as a consequence of the surgery itself that tightens the stabilizing structures. However, a ROM deficit >10 degrees may compromise the functional outcome and participation in sports activities.[30] In the current study, 4 of 20 (20%) patients from the AB group reported a painful ROM deficit >10 degrees, while in the AI group it was observed in only 1 of 19 (5%) patients. This difference could be explained due to the anatomical elements and tissues grasped with each technique. During the AI procedure, the ATFL and occasionally the CFL remnant are addressed in what is considered an anatomical repair of the ligaments.[34] In contrast, the AB is not strictly an anatomic ligament repair, as the sutures grasp the ligament, the capsule, the IER, and/or the sural fascia while tightening these up. In the authors' opinion, by holding these anatomical structures a secondary effect may ensue, creating ROM deficit and possibly scarring in some patients.

The fact that AB is designed to include the IER to the ligament repair is a matter of controversy known from its open Broström counterpart.[4,10] The augmentation using the IER requires the presence of the superolateral IER band, only present in 25% of cases.[10] In addition, an anatomical study observed that the superolateral IER band is a thin and fragile band that may not add significant mechanical contribution to the ligament repair.[10] This could explain why incorporation of the IER in the traditional Broström procedure showed any mechanical advantage when compared with just a ligament repair without the IER.[4] It is likely that during the percutaneous AB step what is actually tightened is not only the IER but also subcutaneous fatty tissue that brings no real stability to the construct.

In the present study both surgeons had more than 3 years of experience and had performed more than 30 cases of the techniques described. However, it is worth mentioning after the publication of a recent study demonstrating the reproducibility of AI[17] that it is still a demanding technique that requires a higher level of expertise in arthroscopy than the AB. The arthroscopic step in the AB is minimal and only aimed at placing anchors onto the fibula. However, the AI procedure is fully performed under direct arthroscopic control. As such, AI is not ideally suitable for the novice ankle arthroscopist. The progress through the learning curve of the surgeon can have implications in the results of the AI technique.

The present study was limited by the fact that a small number of patients were included in each group with no randomization process. Data were collected from 2 different patient cohorts and operating surgeons performing 1 technique each. This may incur a risk of design bias, as may the retrospective nature of the study. However, patients were included consecutively in both cohorts, and surgical indications were the same between the groups. A larger case series with a prospective randomized allocation in groups would certainly improve the validity of the study. Despite the fact that goniometry is commonly used in the clinical setting to measure ankle ROM, the literature suggests that it may not be an accurate measuring method; thus, its use could be considered a limitation.[24] Nevertheless, the same method was used for both groups and the deficit of ankle plantarflexion was also a complaint of the patient. The use of an inclinometer or an automatic device for measurement of ankle ROM could improve the reliability of the measurement and the validity of the study.[35]

Another limitation is that the AOFAS score used is not a validated outcome scale to evaluate ankle instability,[26] and consequently, some clinical aspects may have been overlooked. A specific clinical score to assess ankle instability would have increased the validity of the study.

Conclusion

In conclusion, both the AB and the AI techniques were suitable surgical options to treat chronic ankle instability providing excellent clinical results. However, a higher rate of overall complications was observed in the AB group, particularly involving a painful restriction of ankle plantarflexion and neuritis of the superficial peroneal nerve.

Declaration of Conflicting Interests

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12. Discussion

This PhD thesis is a compendium of publications with four scientific studies on lateral ankle instability, representing a significant advance in the subject. The general purpose was to research the new LCL anatomy concepts described in recent years and their clinical applicability in the surgical field.

Anatomical research fundamentally contributes to the progression of orthopedic surgery by deepening our comprehension of complex structures and their biomechanics. A thorough understanding of the anatomy of the LCL of the ankle is essential for enhancing diagnostic methods and advancing effective conservative and surgical treatments for ankle instability. This detailed anatomical insight enables surgeons to navigate the intricate anatomy of the ankle precisely, thereby reducing the risk of complications and increasing the overall success of surgical procedures. Moreover, a comprehensive understanding of individual anatomical variations allows for personalized surgical approaches. Additionally, anatomical research facilitates the development of innovative techniques and technologies, ultimately improving the quality of care and patient satisfaction.

Ankle sprains, particularly involving the LCL, are a prevalent cause of orthopedic consultations, accounting for about 25% of musculoskeletal injuries. Most (80%) of LCL injuries involve the ATFL, while 20% result in combined damage to the ATFL and CFL. (1) They commonly occur in active individuals, with around 40% of these injuries occurring during sports like basketball, American football, and soccer. Activities that involve sudden stops, changes in direction, or jumping increase the risk of overstretching or tearing these ligaments. (2,3,4) Acute ankle sprains with LCL injuries can significantly impact an individual's quality of life, leading to a high recurrence rate and CAI, requiring surgical treatment. This instability can result in long-term consequences that affect overall patient outcomes. Following an initial sprain, patients face an increased risk of additional injuries, including ankle fractures, cartilage damage to the talus, and syndesmotic injuries, resulting in prolonged pain, functional impairment, and delays in returning to sports. (3, 7)

These factors make the ankle's LCL injuries relevant, justifying the rise of clinical and anatomical studies on this topic in the literature.

The LCL of the ankle has been extensively studied in the last few years. Understanding the anatomy and biomechanics of the LCL and the implications of their injuries is essential for several reasons, especially considering the prevalence of such injuries. (119) This knowledge is vital for diagnosing injuries accurately and developing effective treatment plans. Rehabilitation programs that address the specific muscles and movements associated with the LCL can significantly reduce the risk of recurrence and development of CAI. In cases that need surgical intervention, a proper knowledge of the anatomy allows for precise repairs and ligament reconstructions, minimizing the risk of complications and enhancing patient recovery outcomes.

The ATFL, CFL, and PTFL form the LCL. Initially, these ligaments were described as simple structures that worked separately and independently. Recent anatomical studies have revealed new details about these ligaments' morphology and functional interconnections, providing a detailed understanding that could influence clinical practice.(25, 119) It is well established that the ATFL predominantly comprises two separate fascicles: inferior and superior. Some researchers have suggested that the purpose of the fascicles is to allow penetration of the vascular branches of the anterior fibular artery. (18) Pau Golano et al. observed that the ATFLsup is taut in plantarflex ion while the ATFLinf is in both plantarflexion and dorsiflexion, hypothesizing a different biomechanical purpose for these double fascicles. (18)

The University of Barcelona's anatomy group continued Pau Golano's research on the LCL of the ankle. Through an anatomical study, they investigated the relationship between LCL components, their morphology, and biomechanical function. The first described the components of the ATFL and CFL, determining their anatomical relationships. They showed that the ATFLsup is an intraarticular and distinct anatomical structure that becomes lax in ankle dorsal flexion and taut in plantar flexion. In contrast, ATFLinf and the CFL were isometric and extraarticular structures connected by arciform fibers with a common fibular insertion, forming a functional and anatomical entity named LFTCL complex. (25)

The anatomical and functional differences between the ATFL's superior and inferior fascicles have significant implications for the etiopathology of CAI. For intra-articular ligaments like the ATFLsup, synovial fluid can negatively interfere with the healing process. (46, 47) This fact explains why many patients have chronic symptoms after a sprained ankle. It reinforces the term microinstability, which is used for isolated ATFLsup injuries. In these cases, the patient develops chronic pain and no longer has gross instability because of the intact LFTCL complex. (25, 46) The presence of the LFTCL complex may explain why an isolated repair of the ATFL has excellent results in treating CAI, even when an injury of both the ATFL and CFL exists.

The microinstability concept was also biomechanically tested and proved. A biomechanical study using a robotic system showed that the ATFLsup significantly affected ankle stability, restraining both talar internal rotation and anterior translation. The superior fascicle conferred the most significant restraint to the internal rotation of the talus. This instability increased with additional inversion instability when the inferior fascicle was also sectioned. (23)

The University of Barcelona's anatomy group continued the research on the LCL of the ankle and, through other anatomical research, found new connections between them. (24) Forty fresh-frozen ankle specimens were dissected by separating the ankle's distal fibula so that the ankle's LCL could be observed both from the lateral and medial aspects. They observed interconnections between the LCL's three components from the fibula's medial aspect. Connections were observed between ATFL and PTFL, ATFL and CFL, and CFL and PTFL in all ankles studied. ATFsup and PTFL connections were observed in 42.5% of specimens, while ATFLinf and PTFL connections were present in all specimens. This data could explain the restricted range of motion observed in some arthroscopic all-inside ATFL repair cases. When the ligament is repaired, the increased tension on the connecting fibers could tension the other ligaments, restricting the ankle joint plantar flexion. (24)

The study further highlighted the importance of the medial articular surface shape of the lateral malleolus in influencing the presence of medial connecting fibers between the ATFLsup and the PTFL. Specifically, it was observed that an acute vertex in the articular surface correlated with the absence of these medial connecting fibers. Conversely, these fibers were consistently present when the vertex appeared less acute. This finding suggests that imaging studies documenting the shape of the medial facet could serve as a valuable tool in predicting the presence or absence of medial connecting fibers. Such information could be important for surgeons in assessing the ligamentous structure and planning appropriate interventions. (24)

These anatomical studies were critical to the knowledge and brought new concepts and perspectives in treating ankle ligament lesions. They allowed the improvement of the diagnostic and therapeutic modalities used for CAI and the development of new ankle arthroscopy techniques. Despite this, some shortcomings and anatomical issues encouraged the development of this thesis. Firstly, there was no biomechanical evaluation of the LCL connections, mainly because it is unknown if they are strong enough to create tension between both ligaments when it is under traction. Secondly, the medial connections of the LCL on the fibula were found through a manual dissection. Although a highly experienced anatomist performed all the dissections, this study is limited by the intrinsic difficulty of dissecting this anatomical area and the fact that the medial connections are synovialized. Beyond that, most anatomical studies of the LCL focused on analyzing their length, width, and bone landmarks. They were carried out in a 2D view with a digital caliper or goniometer and did not consider the medial side of the fibula. These questions encouraged the emergence of this thesis, which is a continuation of the anatomical studies of the University of Barcelona's anatomy group. Compared to the existing literature, the scientific studies presented in this thesis are the first to address these gaps. They significantly contribute to clarifying the new anatomical concepts of lateral ankle ligaments that have emerged in recent years.

Understanding the mechanical relationships between the ankle's LCL is crucial for knowledge of the pathogenesis, diagnosis, and treatment of CAI. When surgical intervention is necessary, the LFTCL complex works as a functional unit, meaning an intervention affecting one component will inevitably influence the remaining components. However, the robustness of the connective fibers in transmitting tension from the ATFL to the CFL was unknown.

This thesis evaluated the capacity of the connecting fibers between the ATFLinf and CFL to transmit tension through biomechanical analysis. A U-shaped piece of high-grade steel strip with four strain gauges bonded and connected to form a Wheatstone bridge that measured the ligament deformation was used for this study. We found that tension (1 kg weight - 9.8 N) created on the ATFLinf was transmitted to CFL in all specimens, indicating that the arciform fibers are robust enough to transmit tension between the ligaments. This tension transmission is evidenced by a measurable lengthening of the CFL during traction applied to the ATFLinf, suggesting that the forces involved in the injury are also transferred between the two ligaments in the event of a lateral ankle sprain.

This is the first literature study that dynamically examined the LCL connecting fibers. The clinical implications of these findings suggest that the connecting fibers could be leveraged for the indirect repair of the CFL through reattachment of the ATFL. This method may provide a valuable strategy for managing CFL injuries and improving recovery outcomes for patients with lateral ankle sprains. These results support the favorable clinical outcomes associated with isolated ATFL repair techniques in cases of CAI involving injuries to both the ATFL and CFL. Maffulli et al. (122) presented a long-term follow-up of isolated anatomic open repair of the ATFL in 38 physically active patients with mechanical ankle instability. They concluded that this approach is safe and effective and allows a safe return to preinjury sports activity. Similarly, several arthroscopic isolated ATFL repair procedures have been published and have shown promising outcomes. The anatomical results of this research and the data from the literature corroborate the concept that ligaments function as a single, interconnected ligament complex.

Although the objective of this anatomical research was to prove that movement transmission occurs through the connection, we do not know how much strength is necessary to achieve this (although 1 kg weight—9.8 N—was enough in this study) or how this will translate clinically to the patient in the surgical setting, where tissue quality could affect movement transmission.

Another gap in the literature concerns the LCL morphology on the medial side of the fibula. Considering it, this thesis also sought to clarify this point. For this purpose, a cadaveric study with a tridimensional analysis using a light scanner machine was conducted. A total of eleven fresh-frozen ankle specimens were carefully dissected. The calcaneus, talus, and fibula were separated while preserving the footprints of the lateral ligaments. Each bone was then evaluated using a light scanning machine. The resulting scans were transformed into 3D polygonal models. Areas corresponding to the footprints of the talus, calcaneus, and fibula were identified, and their surface area was measured in square centimeters (cm^2).

The analysis showed that the ATFLinf, CFL, and PTFL footprints were continuous at the medial side of the fibula. Additionally, there was a footprint continuity between the ATFLsup and PTFL at the medial side of the fibula in four cases (36%). The key outcome of this study indicated that the ATFLinf, CFL, and PTFL form a continuous fibular footprint on the medial aspect of the fibula. These results imply that the lateral ankle ligament complex consists of two distinct components: the ATFLsup functioning independently as one unit, while the ATFLinf, CFL, and PTFL collectively form a separate ligament complex.

This study marks a significant advancement in understanding the LCL by examining them from a three-dimensional standpoint. Unlike previous research, which primarily relied on two-dimensional methodologies (28, 123), this research utilizes a more comprehensive digital mapping technique following the complete amputation of bone. Earlier works identified separate fibular attachment points for the ATFL and the CFL (28), contradicting the conclusions drawn in this thesis. The findings from this research further support the concept of the lateral LFTCL complex, as introduced by Vega et al. (25), indicating that the PTFL should also be considered a component of this complex.

The analytical approach taken to assess the footprints of these ligaments is of utmost importance, as it can considerably influence the findings. Traditional two-dimensional measurements using digital calipers may miss critical interconnections between the ligaments. Notably, Neuschwander et al.(124) performed the only existing 3D assessment of the footprints of the ATFL and CFL, discovering a shared confluent footprint on the anterior side of the distal fibula. However, their research did not separate the fibula from the talus and calcaneus, omitted the PTFL, and primarily used hand-drawn diagrams to mark the footprints. This made the analysis subjective, omitting the medial side of the fibula. In contrast, this thesis reveals that the ATFL, CFL, and PTFL footprints are interrelated, particularly along the medial aspect near the inferior tip of the fibula, with the ATFL situated at the anterolateral edge. These interconnections provide new insights into the anatomical relationships of these ligaments and their implications for clinical practices.

The results of this thesis provide crucial insights for diagnosing and treating CAI. They significantly enhance our understanding of ligament anatomy and the mechanisms behind injuries, paving the way for improved imaging techniques like magnetic resonance imaging. Furthermore, this knowledge is invaluable in surgical settings, equipping surgeons with a clear understanding of the complexities of ligament injuries and their distinct characteristics.

This research effectively guides surgical techniques for ligament repair and reconstruction, ensuring that procedures are performed with anatomical precision. Specifically, the evidence strongly supports placing the anchor for the ATFLsup on the anterolateral side of the fibula. Additionally, the anchor for the ATFLinf should be positioned at the inferior tip of the fibula to achieve optimal outcomes. It is important to recognize that placing it on the medial side of the malleolus may lead to further complications.

The study has limitations, including a small sample size and the use of non-laxity ankles, which may not fully represent pathological cases. Additionally, we did not perform a histological analysis of the ligaments. However, it is strengthened by the 3D analysis of ligament footprints after bone amputation, allowing for complete visualization while preserving the ligament remnants. This approach enhances reliability by reducing subjectivity.

Translating these anatomical advances into the surgical field enhanced surgeons' understanding of arthroscopic anatomy, thereby improving surgical techniques for treating ankle instability. Traditionally, the open lateral ligament repair, initially established by Broström Gould, has long been considered the benchmark for surgical intervention in CAI. (125) However, as the significance of addressing associated injuries in CAI has become more evident, ankle arthroscopy has emerged as a crucial component of treatment strategies. (100) Recent advancements in arthroscopic techniques have emphasized reducing invasiveness, shortening recovery periods, and minimizing post-surgical discomfort. (115)

Some researchers have introduced the AB technique to replicate the favorable outcomes associated with the open Broström Gould procedure. This method utilizes a minimally invasive approach, combining arthroscopic guidance for anchor insertion into the fibula with a percutaneous step to secure the lateral ligament and the inferior extensor retinaculum. (94) Although not entirely arthroscopic, this technique marks a significant step forward in the evolution of ligament repair methods.

Clinical and biomechanical studies indicate that the AB technique yields results comparable to the traditional open procedure. (126) Long-term follow-up has also revealed that patients can maintain their athletic pursuits. (127) However, the AB technique is associated with a notable range of complications (5.3% to 29%), primarily due to nerve entrapment or prominent hardware. (128, 129)

Recent advancements in ankle anatomy and improvements in arthroscopic technology have led to significant developments in techniques for repairing ankle ligaments. Based on these advancements, some surgeons have developed specific anatomical approaches and all-inside techniques for arthroscopic ligament repair (115). One such technique, the arthroscopic all-inside repair, explicitly targets the LCL of the ankle to treat CAI. This innovative procedure uses arthroscopic visualization to facilitate accurate and efficient repair of the affected ligaments.

The all-inside method primarily stabilizes the ATFL and the CFL through a minimally invasive approach. It is typically indicated for patients experiencing CAI that has not responded to conservative management strategies. With its focus on precision and targeted intervention, this technique offers a promising option for individuals seeking to restore stability and functionality to their ankles. (130)

However, some surgeons have raised concerns about specific anatomical approaches that do not utilize augmentation. (94) Additionally, all-inside arthroscopic ATFL repair is relatively new and technically challenging. While initial treatment centers have reported excellent outcomes, more extensive case series and comparative research involving alternative arthroscopic techniques are still needed.

Considering the lack of literature, this doctoral thesis included two clinical studies: a series of cases involving all-inside ATFL repair and a comparative study between all-inside ATFL repair and arthroscopic Brostrom.

The all-inside ATFL repair series of cases in this thesis included 18 consecutive patients (11 men and seven women) with a mean age of 36 years old (ranging from 21 to 56). In this study, the surgical treatment of CAI performed through the all-inside arthroscopic ATFL repair technique presented good clinical and functional results. The clinical evaluation revealed a mean visual analog pain score (VAS) result of preoperative pain of 5.0 and a post-operative mean of 0.55. The American Orthopaedic Foot and Ankle Score (AOFAS) pre-operative mean was 69.67 points, and the postoperative mean was 98.17 points, representing an increase of 28.50 points. The range of motion assessment of the ankle showed a difference of 5° in five patients and 10° in one patient. All the patients presented restoration of ankle stability and could return to sports activities. These findings were accompanied by a low complication rate (5%) represented by one patient with transient neuropraxia of the superficial fibular nerve.

This is the first series of the all-inside arthroscopic repair of the ATFL from a nonoriginator center. The results obtained in this thesis enhance the effectiveness and safety of this anatomical and purely arthroscopic technique for treating CAI, as previously detailed. Vega *et al.* showed a series of cases consisting of 16 patients with CAI treated by the all-inside arthroscopic ATFL repair technique, obtaining an increase in the AOFAS from 67 to 97 points without any case of recurrence. (116) Guelfi et al. also evaluated 25 patients with CAI with a mean follow-up time of 34 months. They restored stability in all cases with improved AOFAS from 60 to 94 points and VAS reduction from 6 to 0.9 points. (130)

There is a link between this series of cases and the anatomical studies described in this thesis. Most patients of this series presented isolated lesions of the ATFL, while one-third presented combined lesions of the ATFL with the CFL. In all patients, an isolated ATFL repair was realized. The anatomical research of this thesis demonstrated that the CFL is connected to the ATFL, transmitting tension between both ligaments. Thus, it was considered that arthroscopic repair of the ATFL also implies the tensioning of the CFL in cases where it was injured without impairing the final stability of the procedure. Although some authors criticized the use of anatomical techniques that do not involve the use of the extensor retinaculum and CFL (94), concomitant lesions of the ATFL and CFL may not be a contraindication to performing this technique.

Regarding complications, one patient (5%) presented with neuropraxia of the SPN, which resolved spontaneously. Similar complication rates have also been reported in other case series that evaluated this arthroscopic all-inside ATFL repair.

We believe that the arthroscopic all-inside ATFL repair presents a lower risk of SPN incarceration because the suture and reattachment of the ATFL were conducted solely within the joint under direct arthroscopic vision.

The series of cases has several limitations, including the inability to quantitatively assess pre-operative and post-operative instability, the absence of a control group treated with an open approach, and a short mean follow-up time for evaluating complications. Furthermore, pre-operative ankle range of motion (ROM) was not assessed, and the AOFAS scale is not validated for ankle instability, which may overlook important clinical features. Additionally, the sample was heterogeneous, combining patients with isolated ATFL lesions and those with both ATFL and CFL lesions.

Another study of this thesis was a comparative analysis of all-inside ATFL repair and AB. Patients with CAI were divided into two groups: the first underwent the AB, and the second underwent the arthroscopic all-inside ligament repair. The most important contribution is that both AB and arthroscopic all-inside repair demonstrated similarly excellent clinical results according to AOFAS and VAS scores. However, AB entails a higher potential risk of complications. Eight complications (40%) were recorded at the final follow-up in the AB group. Four patients (20%) presented a deficit in ankle plantarflexion >10 degrees compared with the contralateral side, complaining of mild discomfort or pain when plantarflexing the ankle, and it was considered a minor complication. A transient neuritis of the SPN was experienced in 3 patients (15%). In 1 case (5%), the prominent suture knots required anchor removal 4 months after surgery. Regarding the arthroscopic all-inside repair group, only one complication (5.3%) involving painful ankle plantarflexion deficit >10 degrees was observed and was considered a minor complication. No cases of neuritis, anchor prominence, or other complications were noted.

The literature highlights a significant contrast between the two techniques regarding complication rates. The AB technique has been associated with notably higher complication rates, ranging from 5.3% to 29% (94, 127, 128). Among the complications, the most reported issues include neuritis of the superficial peroneal nerve and discomfort resulting from a visible anchor or suture knot. This thesis corroborates the trend noted in prior research, with a complication rate of 40% linked to the AB technique. Attempts have been made to outline a "risk-free" zone within this technique. Yet, we propose that nerve complications arise primarily due to the suture's passage through the anterolateral region of the ankle. The SPN has various anatomical configurations and a course that can shift with changes in ankle dorsiflexion. These variations increase the risk of injury when sutures are placed subcutaneously. Furthermore, the nerve tends to move approximately 2.4 mm laterally during dorsiflexion compared to when the ankle is in a plantarflexed and inverted position. (106) In contrast, the arthroscopic all-inside repair technique is entirely arthroscopic, allowing for intra-articular grasping of the ligament under direct visualization, thus eliminating the possibility of nerve entrapment beneath the skin.

Regarding post-operative stiffness, some degree of limited range of motion can be a natural outcome of the surgical procedure, which aims to tighten the stabilizing structures. However, if the range of motion deficit exceeds 10°, it could hinder functional recovery and participation in sports activities. In the present study, four out of 20 patients (20%) in the AB group experienced a symptomatic range of motion limitation beyond 10°. In contrast, only one out of 19 patients (5%) in the arthroscopic all-inside repair group reported similar issues.

This discrepancy may be attributed to each surgical technique's different anatomical structures and tissues. The all-inside method focuses on anatomical repair by explicitly addressing the ATFL and, when necessary, the remnants of the CFL. Conversely, the AB technique does not prioritize precise anatomical ligament repair; instead, it involves suturing through the ligament, the joint capsule, the IER, and/or the sural fascia. Tightening may lead to secondary complications, including a reduced range of motion and possible scarring in some individuals.

This clinical study faced limitations due to the small number of patients in each group and the lack of randomization, as data were collected from two different cohorts with surgeons performing a single technique. This design may introduce bias, though patients were included consecutively and had similar surgical indications. A larger, prospective, randomized study would enhance its validity. Additionally, while goniometry is often used to measure ankle range of motion, it may not be entirely accurate. Despite this, it was consistently used for both groups, and the patients' reported deficits in ankle plantarflexion. Using an inclinometer or an automatic measuring device could improve the reliability of the measurements and the overall study validity.

13. Conclusion

1. The connecting fibers between the inferior fascicle of the anterior talofibular ligament and the calcaneofibular ligament are robust enough to transmit tension from one structure to the other.

2. The tridimensional analysis of the lateral ligaments of the ankle demonstrates that the inferior fascicle of the anterior talofibular ligament, the calcaneofibular ligament, and the posterior talofibular ligament have a continuous footprint at the medial side of the fibula.

3. The arthroscopic all-inside anterior talofibular ligament repair was a successful surgical treatment for chronic lateral ankle ligament injury, restoring stability, achieving good clinical results, and being associated with a low complication rate.

4. The arthroscopic all-inside anterior talofibular ligament repair technique is a suitable surgical option for treating chronic ankle instability, offers excellent clinical results, and has lower morbidity than arthroscopic-assisted techniques.

14. References

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