

Strain patterns in normal anterior talofibular and calcaneofibular ligaments and after anatomical reconstruction using gracilis tendon grafts: A cadaver study

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Abstract

Background

Inversion sprains of the lateral ankle ligaments often result in symptomatic lateral ankle instability, and some patients need lateral reconstruction surgeries to reduce pain, improve function, and prevent subsequent injuries. Although anatomically reconstructed ligaments should behave in a biomechanically normal manner, previous studies have not measured the strain patterns of the anterior talofibular (ATFL) and calcaneofibular ligaments (CFL) after anatomical reconstruction. This study aimed to measure the strain patterns of normal and reconstructed ATFL and CFLs using a miniaturization ligament performance probe (MLPP) system.

Methods

The MLPP was sutured into the ligamentous bands of the ATFLs and CFLs of three fresh-frozen, lower extremity, cadaveric specimens. Each ankle was manually moved from 15° dorsiflexion to 30° plantar flexion, and a 1.2-N m force was applied to the ankle and subtalar joint complex.

Results

The normal and reconstructed ATFLs exhibited maximal strain (100) during supination in three-dimensional motion. Although the normal ATFLs were not strained during pronation, the reconstructed ATFLs demonstrated relative strain values of 16–36. During axial motion, the normal ATFLs began to gradually tense at 0° plantarflexion, with the strain increasing, as the plantarflexion angle increased, to a maximal value (100) at 30° plantarflexion; the reconstructed ATFLs showed similar strain patterns. The normal CFLs exhibited maximum strain (100) during plantarflexion-abduction and relative strain measurements of 30–52 during dorsiflexion in three-dimensional motion. The reconstructed CFLs exhibited the most strain during dorsiflexion-adduction and demonstrated relative strain measurements of 29–62 during plantarflexion-abduction. During axial motion, the normal CFLs began to gradually tense at 20° plantarflexion and 5° dorsiflexion.

Conclusion

Our results showed that the strain patterns of reconstructed ATFLs and CFLs are not exactly the same as those in the normal ligaments.

Background

Inversion sprains of the lateral ankle ligaments may result in symptomatic lateral ankle instability that is resistant to treatment in approximately 20% of patients [1–5]. Further, persistent lateral instability of the ankle may lead to osteochondral lesions of the talar dome [6, 7], and eventually result in osteoarthritis of the ankle [8]. Moreover, the pain and instability associated with the compromised ankle biomechanics may decrease the patient's participation in common activities of daily living and sports performance [9].

Therefore, lateral ligament repair or reconstruction may be indicated to reduce pain, improve function, and prevent subsequent injuries should more conservative treatment measures fail.

When performing corrective surgery, a reconstruction technique is indicated if the ligament is absent or insufficient residual ligament is available for repair [10, 11]. Anatomic reconstruction of the lateral ligaments of the ankle, using tendon grafts, is the most commonly used surgical technique [12, 13], and has evolved to become a minimally invasive arthroscopic procedure [14–18]. In this technique, bone tunnels are made at the anatomic origin and insertion points of the ligament, and tendon grafts are then introduced and fixed. Although the anatomically reconstructed ligament is assumed to behave in a biomechanically normal manner, there have not been any publications documenting this assumption.

In this study, a miniaturization ligament performance probe (MLPP) system [19] was used to determine the strain patterns in anatomically reconstructed anterior talofibular ligaments (ATFLs) and calcaneofibular ligaments (CFLs), and the strain patterns were compared with those of normal ATFLs and CFLs.

Materials And Methods

Cadaver description

Three fresh-frozen, through-the-knee, lower extremity cadaveric specimens (two right and one left) were used for this study. The median age of the cadavers, at the time of death, was 63 years (range, 52–70 years); one specimen was from a male and the others from females. The specimens were free of ankle or hind foot deformities, had not undergone prior surgeries or dissections, and did not have histories of trauma or other pathologies that may have altered their anatomy.

The cadaveric studies were performed at the University of Barcelona (Spain); the methods were reviewed and approved by the university's Institutional Review Board. The human materials used in this study were from individuals who, prior to their death, provided informed consent for the storage and use of their bodies for research purposes.

Strain pattern determinations in normal ATFLs and CFLs

In all specimens, the dissections and subsequent strain measurements were performed by one experienced foot and ankle surgeon. An incision was made in the lateral ankle, and the ATFL and CFL were exposed, which the detail described in our previous paper [20]. As the ligaments were investigated as a single unit, they were not isolated after exposure. A force probe was placed into the mid-substance of each ligamentous band of the ATFL and CFL, such that the force probe slit was aligned with the long axis of the ligament fibers (Fig. 1). After introducing the force probe into the ligament, the force probe tube was sutured to the ligament fibers, with 3-0 nylon thread, to prevent rotation of the force probe [19].

An Ilizarov ring-shaped external fixator was placed on the lower leg, and the lower limb was vertically fixed to the measurement desk. A round metal disk (called a “clock”, 150-mm diameter) with 6-mm-

diameter holes placed every 30° around the clock perimeter, was affixed to an acrylic plate (width, 120 mm; length, 280 mm; thickness, 10 mm). The plate was then fixed to the plantar aspect of the foot with a screw (diameter, 6 mm) inserted into the calcaneus and a rod (diameter, 8 mm) inserted between the second and third metatarsals (Fig. 2). This plate had a 25-cm arm to which a 0.5-kg weight could be added to the free end, applying a 1.2-N m force to the ankle and subtalar joint complex ($0.5 \text{ kg} \times 0.25 \text{ m} \times 9.81 = 1.23 \text{ N m}$) [19].

The arm was rotated in 30° increments to allow for strain measurements of each ligamentous band at the various ankle positions. The ankle positions were defined as dorsiflexion when the arm was at the 12 o'clock position, plantar flexion (6 o'clock position), inversion (3 o'clock position), and eversion (9 o'clock position); in addition, the 1 and 2 o'clock positions were defined as dorsiflexion-adduction, 4 and 5 o'clock positions represented supination (plantar flexion adduction), 7 and 8 o'clock positions represented plantarflexion-abduction, and the 10 and 11 o'clock positions were defined as pronation (dorsiflexion-abduction), according to the terminology proposed by the Ad Hoc Committee of Terminology of the Japanese Society for Surgery of the Foot [21].

After determining the strain in each designated ankle position, the strain values of each ligament were also measured during axial motion of the ankle from maximal dorsiflexion to plantar flexion. The angles of the axial, sagittal, and horizontal motions were measured using an electronic goniometer (MPU-9250; TDK InvenSense, San Jose, CA, USA) synchronized to the MLPP system [19].

Strain pattern determinations in the reconstructed ATFLs and CFLs

For each cadaveric limb, after determining the strain patterns of normal ATFLs and CFLs, these ligaments were removed at their origin and insertion points to identify their anatomic footprints. An autologous gracilis tendon autograft (approximately 135 mm long) was harvested from the cadaver's ipsilateral knee. The graft was prepared in an anatomic "Y" configuration, with graft loops at the three ends of the anatomic Y-graft to facilitate suture attachment and graft delivery, as previously described [18] (Fig. 3A).

A guide wire was inserted into the centers of fibular ATFL and CFL origins footprint on the fibular obscure tubercle (FOT) and directed towards the proximal and posterior edges of the fibula at an angle of approximately 30° to the long axis of the fibula, allowing the guide wire to pass through the central portion of the fibula in the coronal axis. The guide wire was passed through the posterior cortex of the fibula and through the skin, posterior to the fibula. Over drilling (6-mm diameter) was then performed to a depth of 20 mm. A talar bone tunnel was constructed to serve as the docking site for the talar stem of the anatomic Y-graft. A guide wire was then inserted to penetrate the talus, through the center of the ATFL insertion footprint, and directed toward the distal end of the medial malleolus. The guide wire was passed through the medial wall of the talus and then through the skin, just anterior and slightly distal to the tip of the medial malleolus. Over drilling was again performed.

A calcaneal bone tunnel was also constructed to serve as the docking site for the calcaneal stem of the anatomic Y-graft. A guide wire was used to penetrate the calcaneal CFL insertion site footprint and directed towards the central posterior cortex of the calcaneus. The guide wire was then over drilled (6-mm diameter) to a depth of 30 mm. The 3 anatomic Y-graft stems were then inserted into their respective tunnels, to a depth of at least 15 mm, and fixed with interference screws. Each bony attachment of the tendon graft was fixed with a 6-mm diameter interference screw while applying a 30-N tension force. First, the fibular stem was fixed, then the talar stem was fixed while the ankle was in a 0°, flexed neutral position. The calcaneal attachment was fixed in a similar manner (Fig. 3B).

After reconstruction of the ATFLs and CFLs, the strain values of the reconstructed ligaments were measured using the MLPP system during axial and three-dimensional motion, similar to the normal ATFL and CFL investigations, previously described (Fig. 3C) [19].

Data analysis

The relationships between the foot positions and the tensile forces of each ligamentous band were analyzed. The tensile force data from the force probe were obtained by synchronizing the arm of the clock, which was manually rotated every 30°, with the movement of the ankle from 15° dorsiflexion to 30° plantar flexion; the movements were repeated 10 times (for each limb) and the strain of each ligamentous band, during ankle motion, was measured. Individual strain data were aligned to reflect the strain relative to the neutral position (0) and to the maximum strain value (100). The average value determined at each position was connected by a line, and the ligament tension patterns were compared between the normal and reconstructed specimens [19].

Results

Strain patterns in normal and reconstructed ATFLs

During three-dimensional motion, the normal and reconstructed ATFLs exhibited maximum strain (100) during supination (Fig. 4). Although the normal ATFL was not strained when in pronation, the reconstructed ATFL did exhibit strain (relative strain values of 16–36) in pronation.

During axial motion, the normal ATFL began to gradually exhibit strain at 0° plantarflexion, with the strain increasing as the plantarflexion angle increased to a maximum (strain value of 100) at 30° plantarflexion (Fig. 5A). The reconstructed ATFL began to tense gradually at 15° plantarflexion, and the strain increased as the plantarflexion angle increased to a maximum strain (100) at 30° plantarflexion. Two specimens showed strain values of 20 and 30 at 15° of dorsiflexion (Fig. 5B).

Strain patterns in normal and reconstructed CFLs

During three-dimensional motion, the normal CFL was under the most strain during plantarflexion-abduction and exhibited less strain (values of 30–52) in dorsiflexion (Fig. 6A). The reconstructed CFL

was under the most strain during dorsiflexion-adduction and exhibited less strain (29–62) during plantarflexion-abduction, which was opposite of the normal strain pattern (Fig. 6B).

During axial motion, the normal CFL began to gradually tense at 20° plantarflexion and at 0° dorsiflexion. The strain increased as the plantarflexion or dorsiflexion angles increased to maximum (100) strain at 15° dorsiflexion or strain values of 55–70 at 30° during plantar flexion (Fig. 7A). The reconstructed CFL began to gradually tense at 0° dorsiflexion, increasing as the dorsiflexion angle increased to a maximum (100) strain at 15° dorsiflexion (Fig. 7A). Unlike the normal CFL, the two reconstructed specimens showed either no strain or a strain value of 35 during plantar flexion (Fig. 7B).

Discussion

This is the first study to comprehensively describe the contributions of reconstructed ATFLs and CFLs to overall ankle stability, in various ankle positions, and to compare the tensile patterns with those generated for normal ATFLs and CFLs.

A previous study evaluated the tensile patterns of normal ATFLs and CFLs during three-dimensional motion, and reported that the maximal tensile force in the ATFL was observed during supination with plantarflexion and that in the CFL occurred during pronation with plantarflexion [22]. These findings are similar to the present findings considering that the terms “supination with plantarflexion” and “pronation with plantar flexion,” used in the previous paper, are analogous to our “supination” and “plantarflexion abduction” terminology, according to the proposed terminology [21].

During anatomical reconstruction of the lateral ankle ligament, bone tunnels are created at the anatomic origin and insertion footprints of the ligament to fix the tendon graft [12–18], thus recreating normal anatomy. In this study, the strain patterns of the reconstructed ligaments were not always the same as those observed in the native, non-reconstructed ligaments. For example, the normal ATFL was not strained during pronation, whereas the reconstructed ATFL demonstrated slight strain, and the normal CFL experienced the most strain during plantarflexion abduction, but the reconstructed ATFL exhibited the most strain during dorsiflexion adduction. These strain pattern differences may be attributed, in part, to slight anatomical variations that are introduced when a common origin site is used (as in the present study) as the origin of the fibular stem of the anatomic Y-graft and as the origin of both the ATFL and CFL, as previously described [18] (Fig. 3A)

If the analogous surgical procedure involving the knee is considered, anatomic anterior cruciate ligament (ACL) reconstruction is defined as the functional reconstruction of the ACL to its native dimensions, collagen orientation, and insertion site [23]. This is similar to the anatomical reconstruction of the ankle lateral ligaments, where a common origin site is used for the fibular stem of the anatomic Y-graft bone tunnel that is at a position midway between the original ATFL and CFL footprints.

In a prior study, the landmarks used to define the centers of the origin and insertion points for the ATFL and CFL demonstrated variability [24]. Further, each footprint has an elliptical shape that varies in area

and positioning during each surgery.

Another explanation for the variability in strain patterns between the native and reconstructed lateral ligaments may be related to the natural variations in the lengths and bundle patterns of the native ligaments. For example, cadaveric studies have revealed that the ATFL may exist as a single bundle (31–38% of specimens), 2 bundles (50–60%), or 3 bundles (9–12%) [25, 26]. However, a single bundle reconstruction technique was adopted in this study, and is used in most anatomical reconstruction techniques; multiple band anatomical reconstruction techniques are not currently used. Another concern is that the normal ATFL and CFL work co-operatively with the lateral talocalcaneal ligament and the 3 ligaments have a single-unit shape [27, 28]; however, the ATFL and CFL are reconstructed as solitary ligaments.

The ultimate goals of reconstructive surgery are to diminish pain and improve function, and previous reports have shown good clinical results after conventional anatomical reconstruction of the ATFL and CFL [12, 13]. Therefore, the goal of restored biomechanics may not be essential, but the development of a reconstructive surgery technique that aims to restore more normal biomechanics should be considered.

Limitations

The small size of this study is a potential source of error. The methods described for this study dictated that the measurements for one limb required one full day to complete. Regardless, an increased sample size would reduce the associated error.

Conclusions

This study demonstrated the biomechanical properties of each ligamentous band of normal and anatomically reconstructed ATFLs and CFLs. The results showed that the strain patterns of reconstructed ATFLs and CFLs were not exactly the same as for the normal ligaments. These findings provide a biomechanical framework for future studies aimed at improving ankle biomechanics following stabilization surgeries that seek to diminish pain and improve function in the ankles of patients with chronic ankle instability.

List Of Abbreviations

MLPP

Miniaturization Ligament Performance Probe

ATFL

Anterior talofibular ligament

CFL

Calcaneofibular ligament

Declarations

Ethics approval and consent to participate

This cadaveric study was approved by the Institutional Review Board of the University of Barcelona and conducted in accordance with the bylaws of the Bioethics Committee of the “Unitat d' Anatomia i Embriologia humana” of the Faculty of Medicine, University of Barcelona, Spain (Campus Clinic). Consent for the storage and use of the bodies for research purposes was given by all body donors before death or by their next of kin.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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All authors have no financial relationships relevant to this article to disclose.

Authors' contributions

MT, SO, XO, and MG designed the study; MT, SO, XO, TY, YT, MK, DL, KM, MK, and MG performed the research; and RI wrote the first draft. All authors read and approved the final manuscript.

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Figures

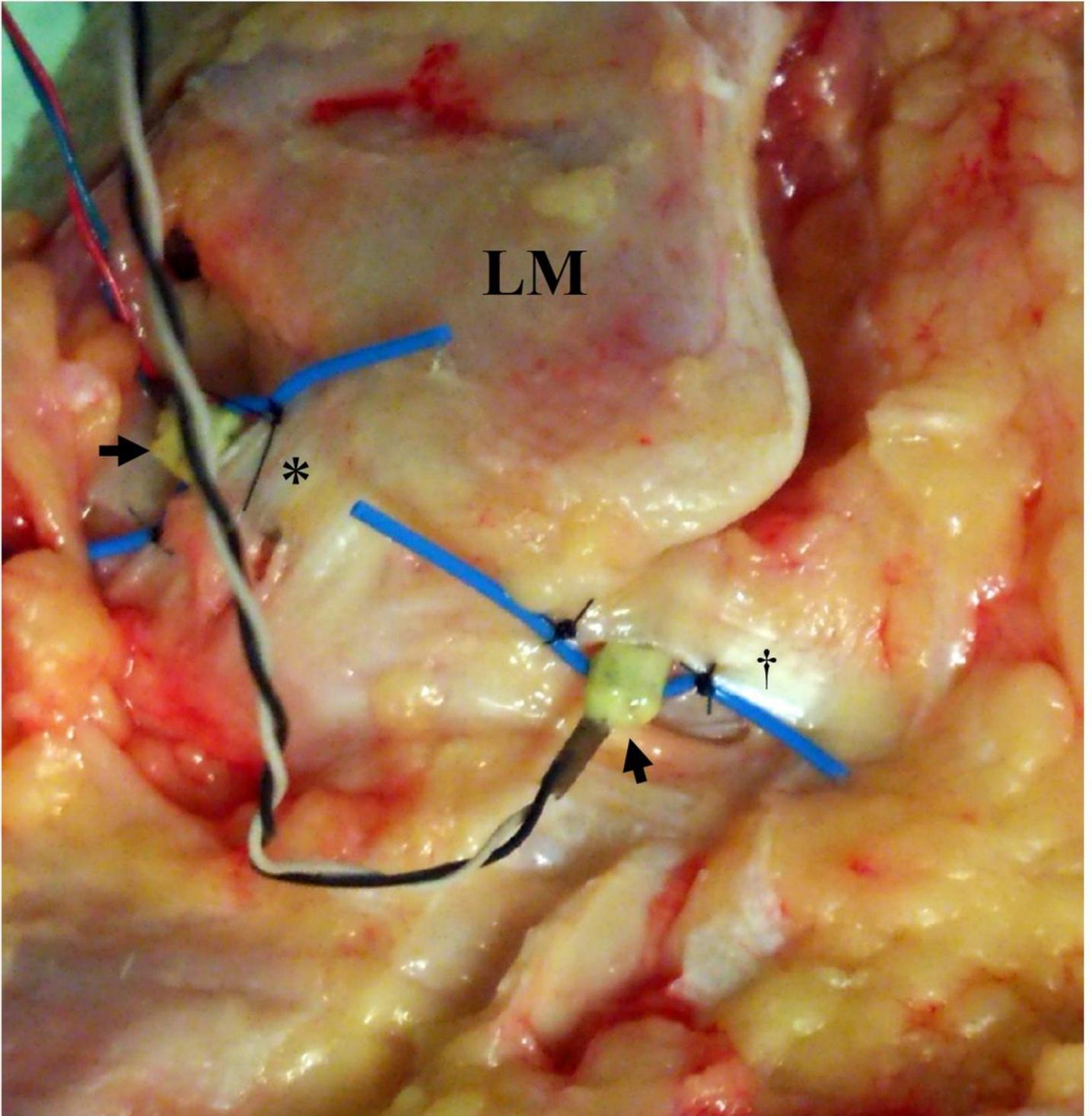


Figure 1

Force probes in normal anterior talofibular (ATFL) and calcaneofibular (CFL) ligaments. A force probe (arrow) is shown inserted into the mid-substance of each ligamentous band of the ATFL (*) and CFL (†).

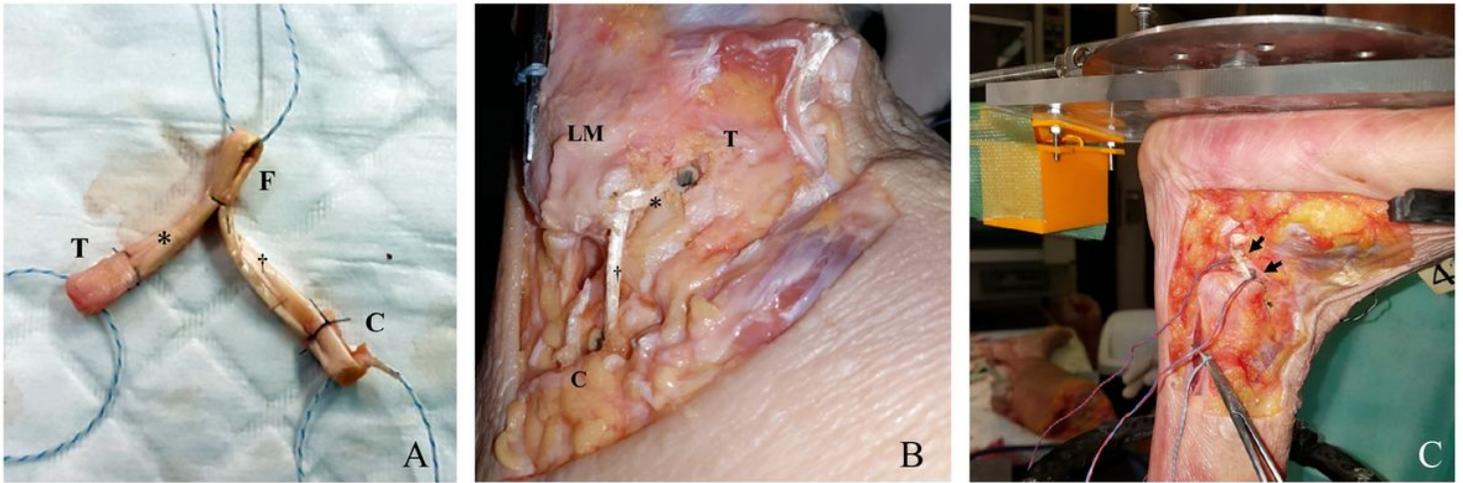


Figure 3

Anterior talofibular (ATFL) and calcaneofibular (CFL) ligament reconstruction. (a) Anatomic Y-configuration tendon graft. The graft is prepared in an anatomic “Y” configuration with graft loops at the three ends (F, fibular limb; T, talar limb; C, calcaneal limb) of the anatomic Y-grafts of the ATFL (*) and CFL (†). (b) Reconstructed ATFL (*) and CFL (†). (c) force probes (arrow) inserted into normal ATFL and CFL. LM, lateral malleolus; T, talus; C, calcaneus

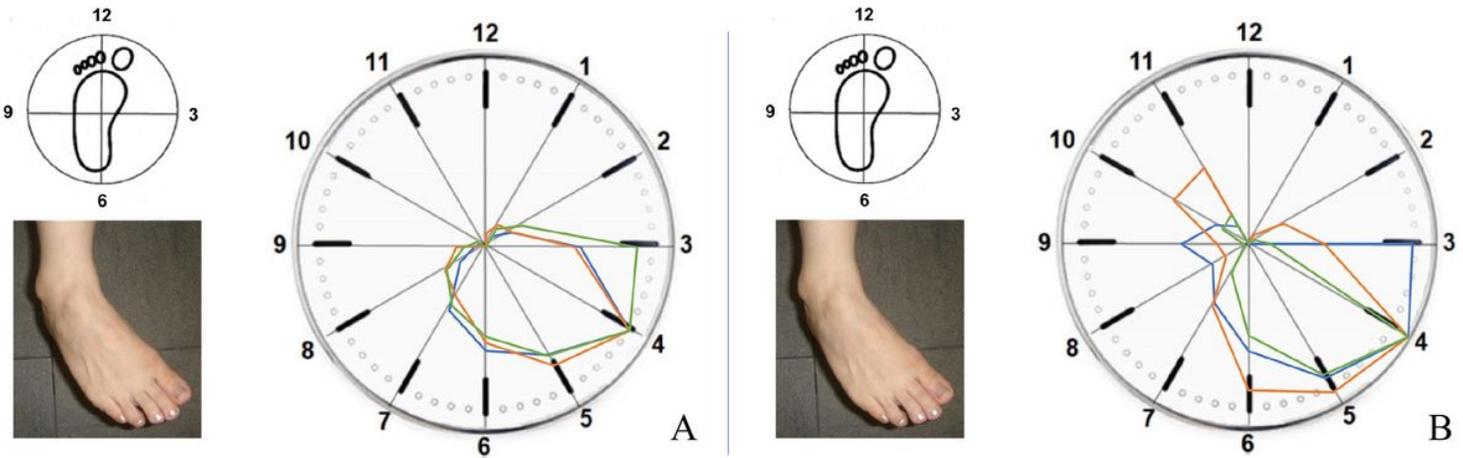


Figure 4

Strain patterns of normal and reconstructed anterior talofibular ligaments (ATFLs) during three-dimensional motion. (a) The normal ATFL exhibited maximal strain (strain value, 100) in supination. (b) The reconstructed ATFL also exhibited maximal strain (100) in supination. Although the normal ATFL does not exhibit strain in pronation, the reconstructed ATFL shows strain values of 16–36 in pronation.

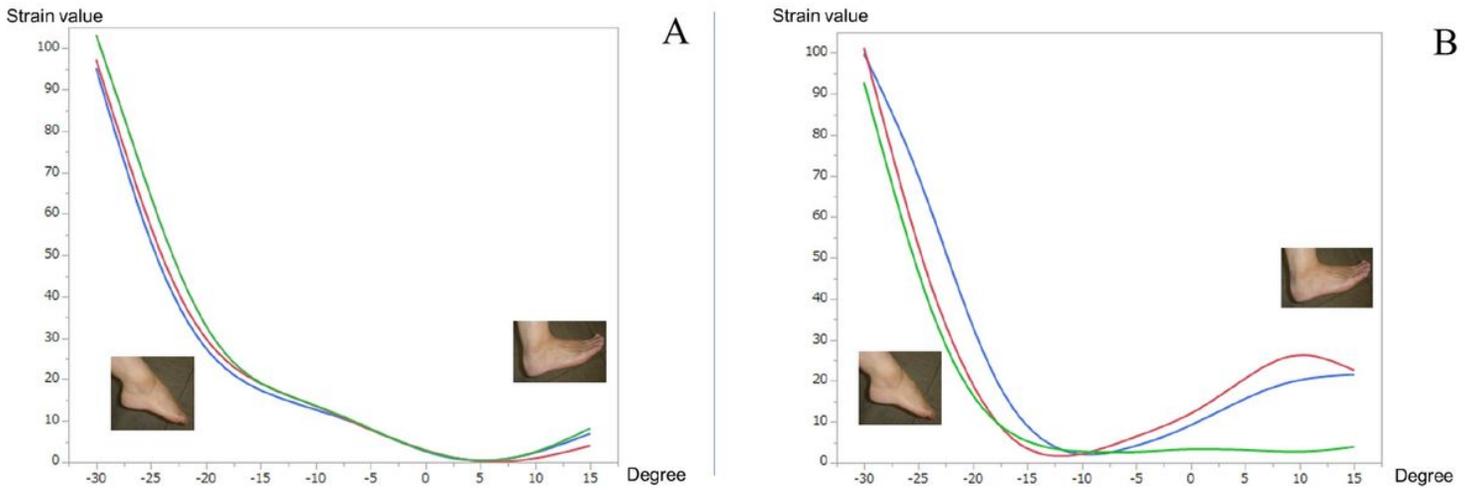


Figure 5

Strain patterns of the normal and the reconstructed anterior talofibular ligaments (ATFLs) during axial motion. (a) The normal ATFL starts to gradually tense at 0° plantarflexion, with the strain increasing as the plantarflexion angle increases to a maximum strain (100) at 30° plantarflexion. (b) The reconstructed ATFL starts to gradually tense at 15° plantarflexion, with strain increasing as the plantarflexion angle increases to a maximum strain (100) at 30° plantarflexion.

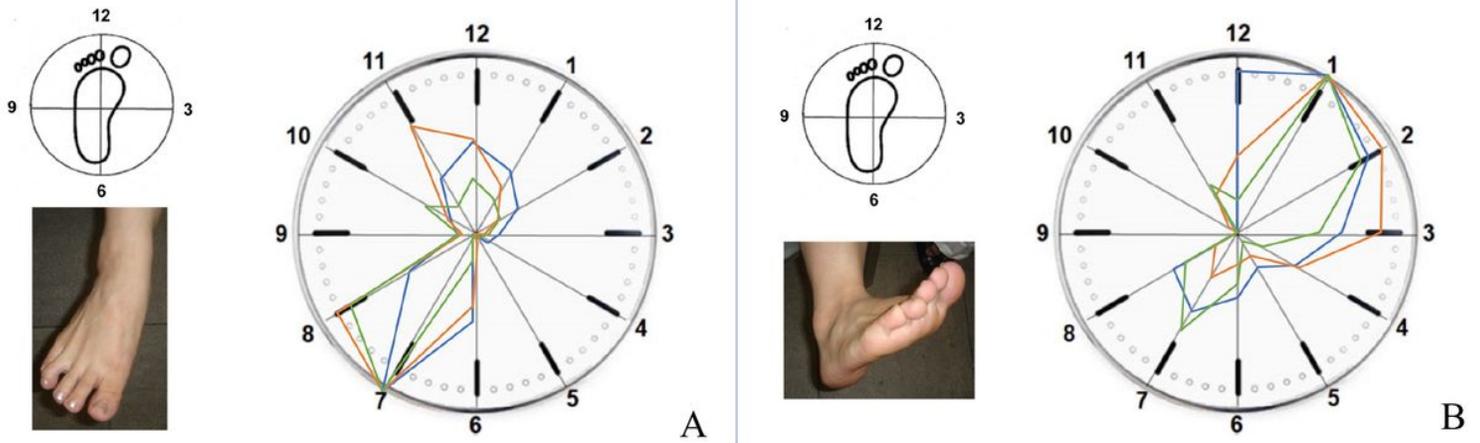


Figure 6

Strain patterns of normal and reconstructed calcaneofibular ligaments (CFLs) during three-dimensional motion. (a) The normal CFL exhibits the most strain during plantarflexion-abduction, with strain values of 30–52 during dorsiflexion. (b) The reconstructed CFL exhibits the most strain in dorsiflexion-adduction, with strain values of 29–62 during plantarflexion-abduction.

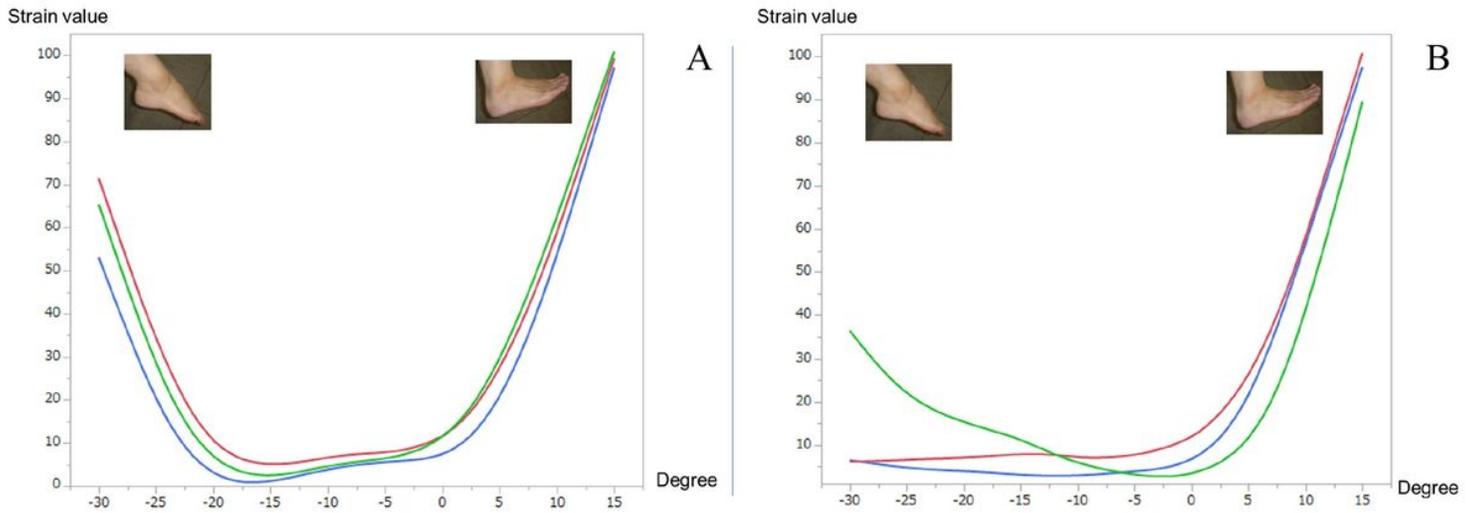


Figure 7

Strain patterns of normal and reconstructed calcaneofibular ligaments (CFLs) during axial motion. (a) The normal CFL begins to gradually tense at 20° plantarflexion and 5° dorsiflexion. The strain increases as the plantarflexion and dorsiflexion angles increase. The maximum strain (100) occurs at 15° dorsiflexion, with a relative strain value of 70 at 30° plantar flexion. (b) The reconstructed CFL gradually increases in tension beginning at 0° dorsiflexion, with the strain increasing as the dorsiflexion angle increases; maximum strain (100) occurs at 15° dorsiflexion. Two specimens did not show any strain and one exhibited a strain value of 150 during plantar flexion.