

The miniaturization ligament performance probe (MLPP) system for analysis of the ligament strain pattern in three-dimensional motion of the ankle

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Abstract

Background Measuring strain patterns of joint ligaments in various positions helps in understanding their function. There are few studies on biomechanical properties of ankle ligaments, and the tensile properties of each ligament during motion have not been described because the existing biomechanical sensors are too big to insert into the ankle. **Hypothesis/Purpose:** This study aimed to verify the validity of a novel miniaturized ligament performance probe (MLPP) system in measuring the strain pattern of the anterior talofibular ligament (ATFL) during ankle motion. **Methods** The system is composed of a strain gauge (force probe), an amplifier unit, a display unit, and a logger, which are widely used industrially. Ten fresh-frozen through-the-knee lower extremity cadaveric specimens were used. The MLPP was sutured into the midsubstance of ATFL fibers. To measure the tensile force, a round metal disk (clock) (diameter 150 mm), with a 6-mm-diameter hole every 30°, was fixed on the plantar aspect of the foot. With a 1.2-Nm load applied to the ankle and subtalar joint complex, the ankle was manually moved from 15° dorsiflexion to 30° plantar flexion. The clock was rotated every 30° to measure the strain of the ATFL at each end point detected by the miniature force probe. During the motion from 15° dorsiflexion to 30° plantar flexion, the ATFL tensed near 20° plantar flexion, and the strain increased as the plantar flexion angle increased. The ATFL was maximally tensioned at 3 and 4 o'clock in the inversion position. **Results** In the elastic range where the ATFL can return to its original shape and length, tensile force was proportional to strain in all cases. All specimens showed almost similar strain patterns, with coefficients of variation ranging from zero to one in axial motion and from 0.05 to one in clock motion. **Conclusion** The MLPP system was effective in establishing the relationship between the limb position and ligament strain pattern of the small ligaments of the ankle.

Background

Measuring the strain patterns of joint ligaments in several different positions is necessary to understand their function. Previous publications described the biomechanical properties of large joints by directly measuring the tensile strength of ligaments [1–4]. However, very few studies have explored the biomechanical properties of the ankle [5, 6], and the tensile properties of each ligament during ankle motion have not been described because the existing biomechanical sensors used in large joint research are too big to fit into ankle ligaments.

We previously used a custom-made ankle ligament testing device [6]. The device directly measured the load on each ligament of the ankle using a small force probe in a custom-made ankle ligament and clarified the tensile pattern of the anterior talofibular, calcaneofibular, posterior talofibular, and tibiocalcaneal ligaments in passive circumferential rotating motions of the ankle and subtalar joints. However, because the sensors were custom-made, it was difficult to use under other conditions.

In this study, we developed a novel miniaturized ligament performance probe (MLPP) that can be inserted into small ligaments to allow the measurement of their biomechanical properties. We aimed to verify the

validity of the MLPP in measuring the strain pattern of the anterior talofibular ligament (ATFL) during ankle motion.

Methods

Structures of the MLPP system

The MLPP system is composed of a strain gauge (force probe), an amplifier unit, a display unit, and a logger (Fig. 1). This system is capable of detecting small changes in resistance using the force probe. These changes in resistance are then enlarged by the bridge of the amplifier unit and then transferred to the output of the display unit where analog-to-digital conversion takes place, and subsequently, the amount of strain is displayed. This strain measurement is converted to analog, and its voltage is finally recorded in the logger.

The force probe (Showa Unilateral Strain Gauge; Showa Measuring Instruments Inc., Tokyo, Japan) is rectangular (width, 2 mm; height, 1.5 mm; length, 8 mm) and has a tubular structure, with slits entering vertically on one side of its surface (Fig. 2A and B). In the force probe, the internal strain gauge is distorted by applying force in a certain direction, thus allowing strain to be measured. When the force probe is inserted in the tissue, it may rotate as forces are applied and could reduce or invert the output (Fig. 3A and B). To suppress this rotational influence, a tube for preventing rotation was attached to the force probe, and both ends were sutured to the tissue to be measured (Fig. 4).

A performance cube was used to measure the position of the ankle (Fig. 5). It is composed of a nine-axis sensor (MPU-9250), a microcontroller (ESP32), and a logger. MPU-9250 and ESP32 are loaded in the performance cube. The MPU-9250 is a sensor that records position information, and it can acquire the values of nine axes in total, it also records angular acceleration and geomagnetism. The MPU-9250 is equipped with a digital motion processor, which automatically measures motion at the time of sensor initialization and determines posture. ESP32 is a microcontroller that calculates data obtained from MPU-9250 and transmits data to the logger using a wireless module. This performance cube is synchronized with the MLPP system.

Source of cadaver

Six fresh-frozen through-the-knee lower extremity cadaveric specimens were used for this study (three right and three left). Three specimens were from male and three were from female cadavers. The median age was 64 years (range 46–82 years). These specimens were free of ankle or hindfoot deformity, did not undergo surgery or dissection, and did not have any history of trauma or other pathology that may alter the anatomy. All cadaveric studies were performed at University of Barcelona in Catalonia, Spain. All methods in this study were reviewed and approved by the institutional review board of The University of Barcelona. Consent for the storage and use of the bodies for research purposes was given by all body donors prior to death or by their next of kin.

Experiment on strain pattern of the ATFL

The subsequent procedures were performed in all specimens by an experienced foot and ankle surgeon. An incision was made in the lateral ankle, and the ATFL was exposed. A force probe was placed in a force probe tube in the midsubstance of the ATFL to align the slit of the force probe with the long axis of the ligament fiber. After introducing the force probe into the ligament, the force probe tube was sutured to the ligament fibers with a 3 – 0 nylon thread to prevent the rotation of the force probe (Fig. 4).

An Ilizarov ring-shaped external fixator was placed on the lower leg, and the lower limb was fixed vertically to the measurement desk using a vice to allow the localization of the distal upper and proximal lower portions of the specimens. A round metal disk (clock) (diameter 150 mm), with a 6-mm-diameter hole every 30°, was affixed to an acrylic plate (width, 120 mm; length, 280 mm; thickness, 10 mm). This was fixed on 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. 5). This plate has a 25-cm arm where a 0.5-kg weight can be added at its end, thus applying an approximately 1.2-Nm force to the ankle and subtalar joint complex ($0.5 \text{ kg} \times 0.25 \text{ m} \times 9.80665 = 1.2258312 \text{ N m}$). This arm rotates every 30° on the clock and allows the measurement of the strain of the ATFL at each end point (Fig. 6). The ankle positions are defined as dorsiflexion with the arm at the 12 o'clock position, plantar flexion at the 6 o'clock position, inversion at the 3 o'clock position, and eversion at the 9 o'clock position. The angles of axial motion, dorsiflexion, and plantar flexion were measured using an electronic goniometer (MPU-9250; TDK InvenSense) synchronized with the MLPP system.

After all measurements were made in the intact specimens, the ATFL was cut at the fibular attachments, leaving the force probes.

Data analysis

The relationship between the foot positions and the tensile forces of the ATFL was analyzed. The tensile force data from the force probe were obtained by synchronizing the probe with the arm of the clock rotating every 30°. The ankle was moved from 15° dorsiflexion to 30° plantar flexion 10 times manually, and the strain of the ATFL during ankle motion was measured. Individual strain data were aligned with the value at the neutral position (0) and the maximum value (100). The average value at each position was connected by a line, and the ligament tension pattern was compared among the specimens.

Results

In the elastic range where the ATFL can return to its original shape and length, tensile force was proportional to strain in all cases (Fig. 7).

The strain pattern of the ATFL at each end point in all specimens on the motion from 15° dorsiflexion to 30° plantar flexion is shown in Fig. 8A and B and on the clock in Fig. 9A and B. During the motion from 15° dorsiflexion to 30° plantar flexion, the ATFL tensed at around 20° plantar flexion, and the tensile

strength increased as the plantar flexion angle increased. The ATFL was maximally tensioned at 3 and 4 o'clock in inversion position. All specimens showed almost similar strain patterns, with coefficient of variations from zero to one in axial motion and from 0.05 to one in clock motion.

Discussion

Our results showed that the MLPP system was effective in establishing the relationship between the limb position and ligament strain pattern of the ATFL. To gain a comprehensive understanding of individual ligament contribution to overall ankle stability, it is important to understand the biomechanical properties of each individual ankle ligament. By measuring the movement of the ankle, we could assess each ligament's function in various limb positions using the cadaver model.

The results obtained by the MLPP system were similar to those of the system used in a previous study [6]. The sensor used in the MLPP system is widely used in the industry, and its accuracy is guaranteed. In addition, the insertion technique is simple, which helps in measuring the strain pattern of the ATFL during ankle motion.

Previous studies, such as those using Roentgen measurement [7], an Inman ankle machine [8], the magnetic position and orientation tracking system [9], the video-based data collection system [10], and the 3SPACE® FASTRAK® system [11, 12], have been able to directly measure the tension pattern of each ligament in the ankle, but allow only indirect estimations of the biomechanical properties of the ankle ligaments.

For direct measurement of the load on the ligament, it is necessary to insert the sensor into the ligament. DeRouin et al. reported a system that uses a wireless sensor for measuring ligament tensile force in large joints [13]. It has a high-force sensor consisting of a stainless-steel strip with hooks at both ends. Although this system has the advantage of directly measuring the load applied to the ligament, the size of the metal strip ($28 \times 1 \times 0.5$ mm) and the sensor ($20 \times 1 \times 30$ μ m) is too big for a small joint such as the ankle joint.

Limitations

The disadvantage of the MLPP is that it measures the strain value of the ligament instead of tensile force. In the elastic range where the ATFL can return to its original shape and length, force and strain showed a linear proportional relationship. Therefore, it is theoretically possible to convert the strain value to newton-force if Young's modulus is obtained by calibration. However, it is difficult to accurately determine Young's modulus because the water content of the tissue decreases with time and the elasticity of the ligaments changes. The acceptable variation in the results of this study might be influenced by the temporal change in the elasticity of the ligament.

Conclusion

This study described a new MLPP system that effectively established the relationship between the limb position and ligament strain pattern of the small ligaments of the ankle, thus providing a better understanding of the biomechanical function of each ligament of the ankle.

Abbreviations

ATFL: anterior talofibular ligament

MLPP: miniaturized ligament performance probe

Declarations

Ethics approval and consent to participate

This study was a cadaveric study and approved according to 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 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.

Funding

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Authors' contributions

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

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Not applicable.

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Figures

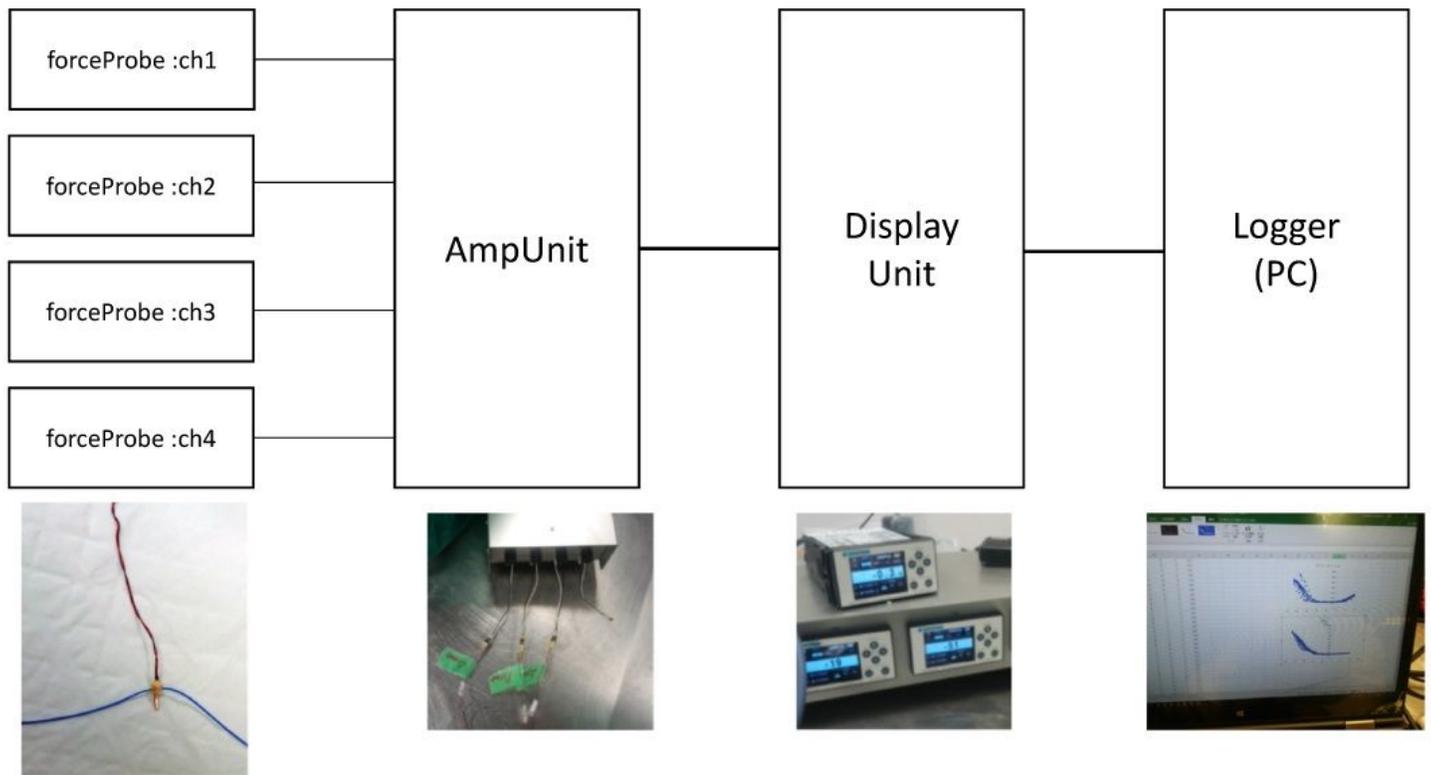


Figure 1

Miniaturized ligament performance probe system. This is composed of a force probe (left), an amplifier unit (middle left), a display unit (middle right), and a logger (right).

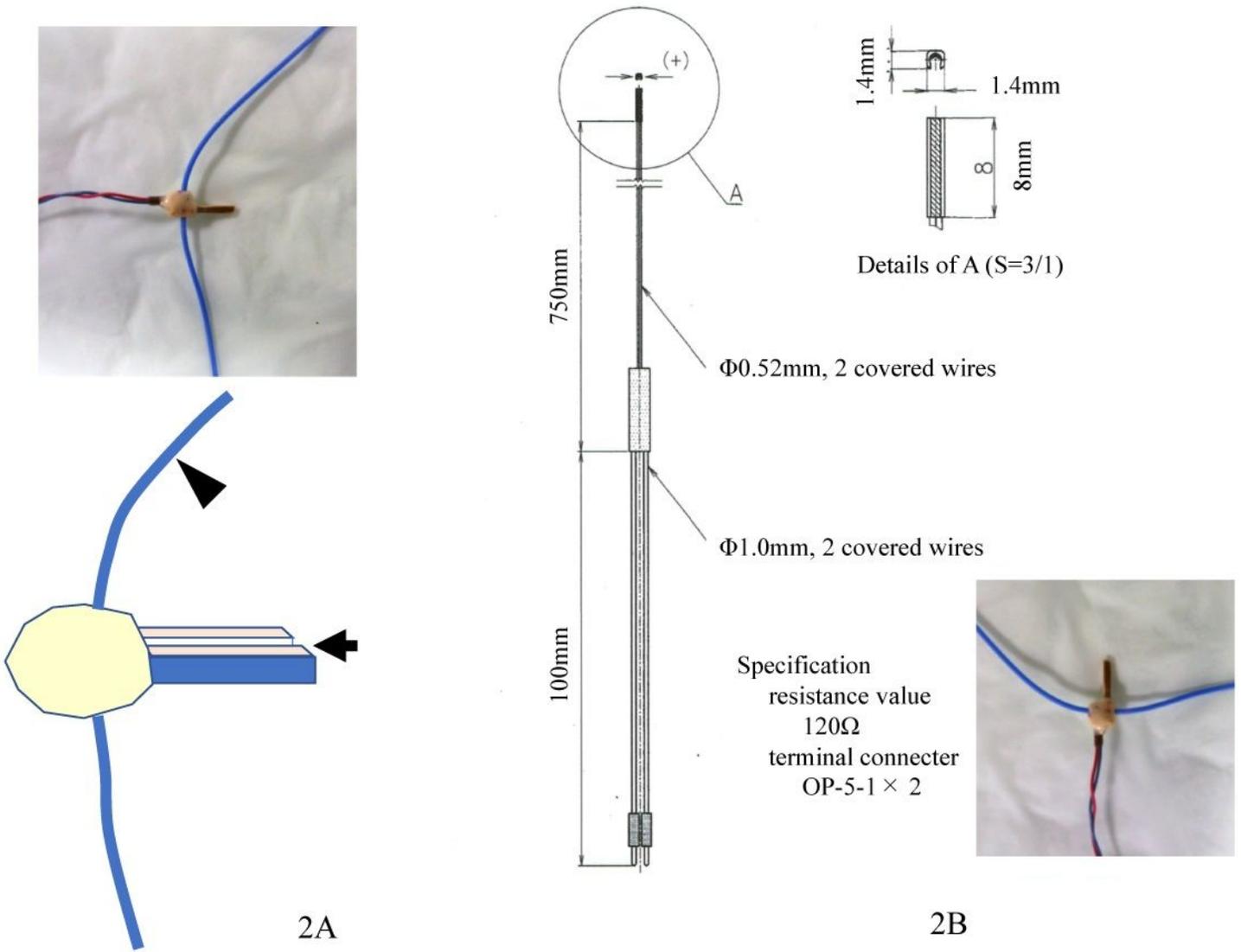
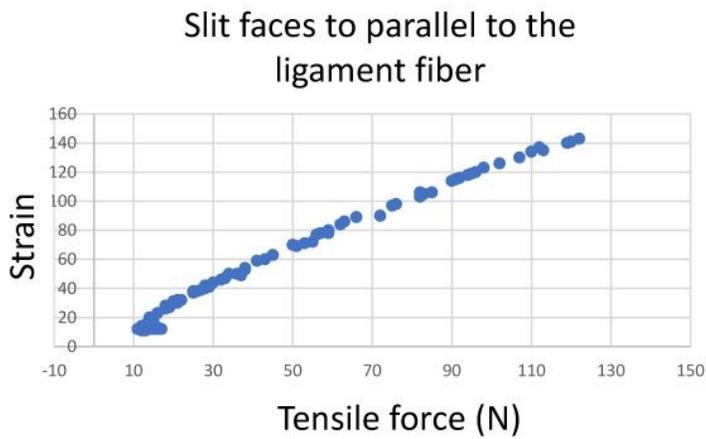
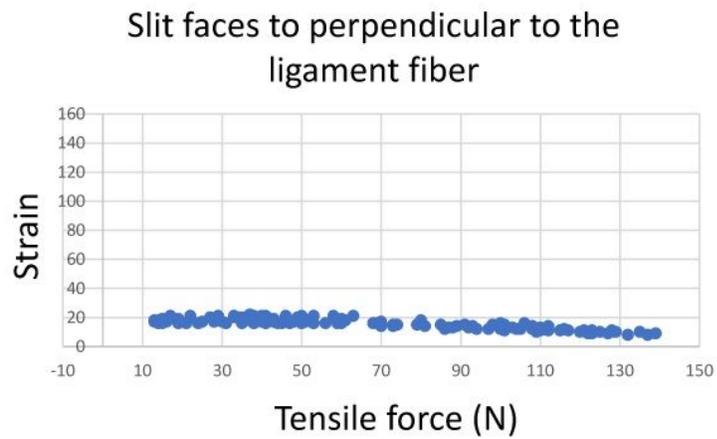


Figure 2

Force probe (strain gauge). The force probe is rectangular shaped (A) and has a tubular structure with slits entering vertically on one side of its surface (B).



3A



3B

Figure 3

Difference in measured value because of difference in the direction of slit of the force probe. The ligament tensile pattern can be measured if the slit of the force probe is parallel to the ligament fiber (A), but not if the slit of the force probe is perpendicular to the ligament fiber (B).

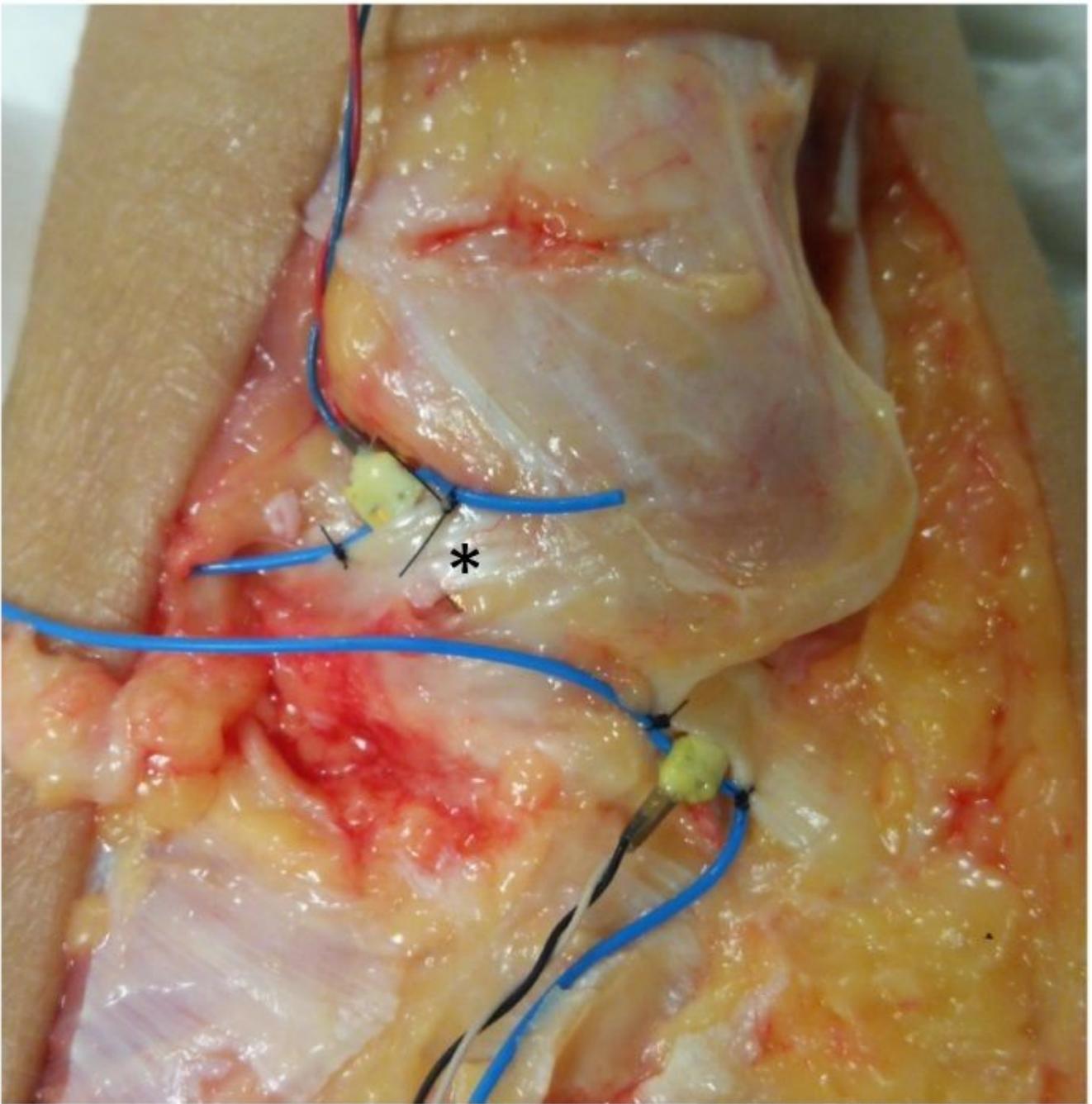


Figure 4

Insertion and fixation of the force probe into the anterior talofibular ligament. Both ends of the tube that prevents rotation of the force probe in the ligament were sutured to the anterior talofibular ligament (*).



Figure 5

Set-up of the specimen. The lower limb is fixed vertically to the measurement desk using an Ilizarov ring-shaped external fixator, and a clock (*) and performance cube (†) are affixed to an acrylic plate.

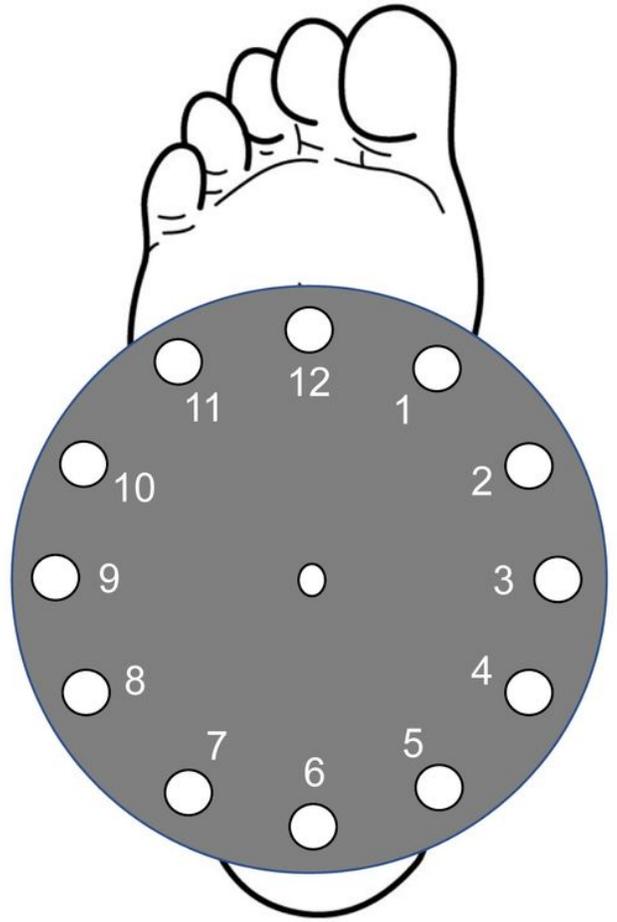
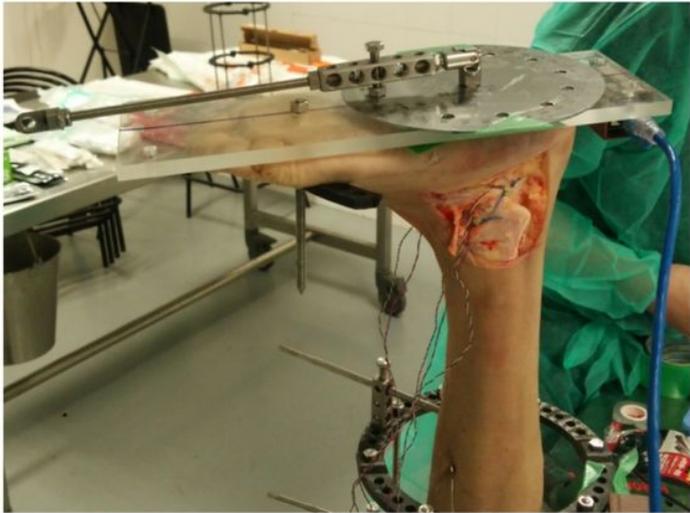


Figure 6

Clock.

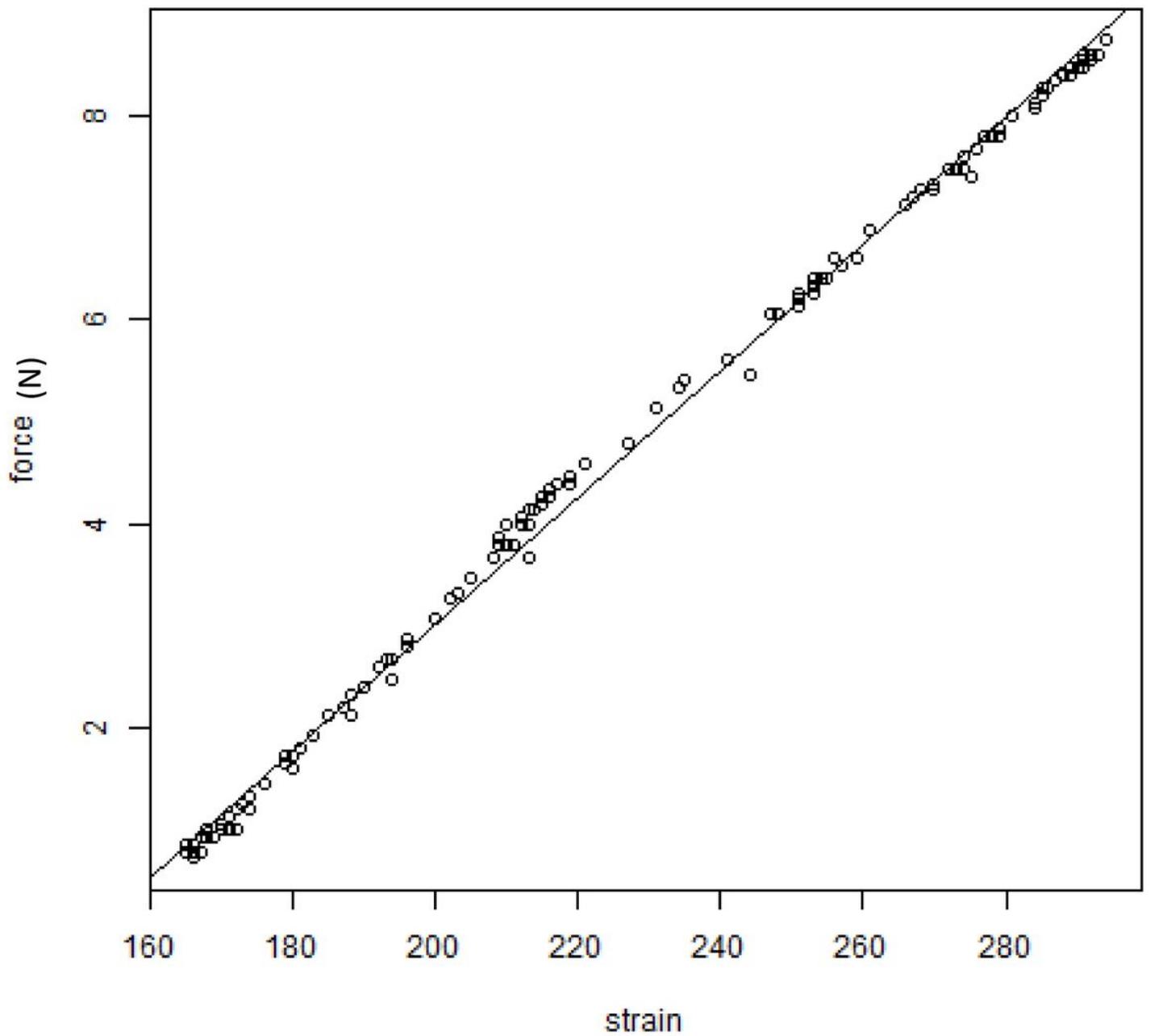
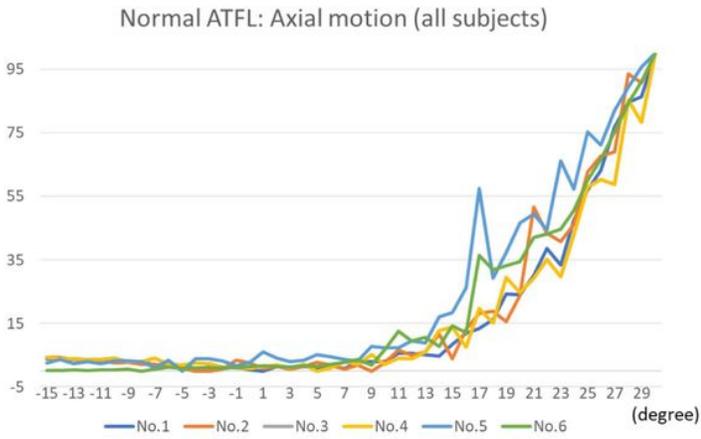
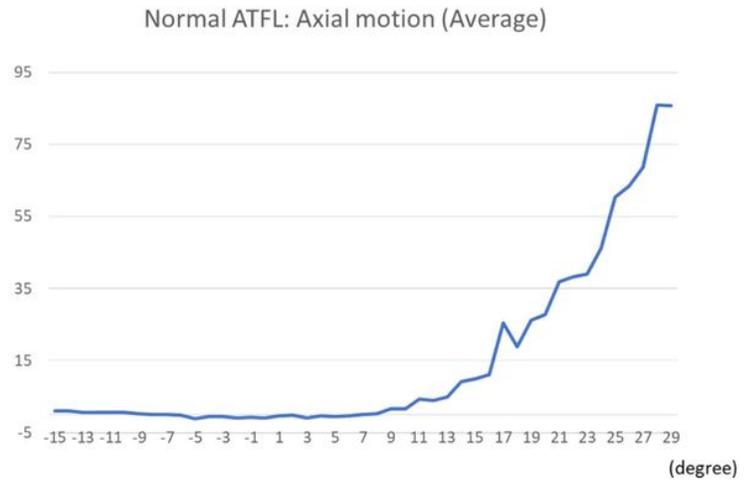


Figure 7

Plot of the tensile force data of the anterior talofibular ligament while moving the ankle from full dorsiflexion to full plantar flexion (10 times).



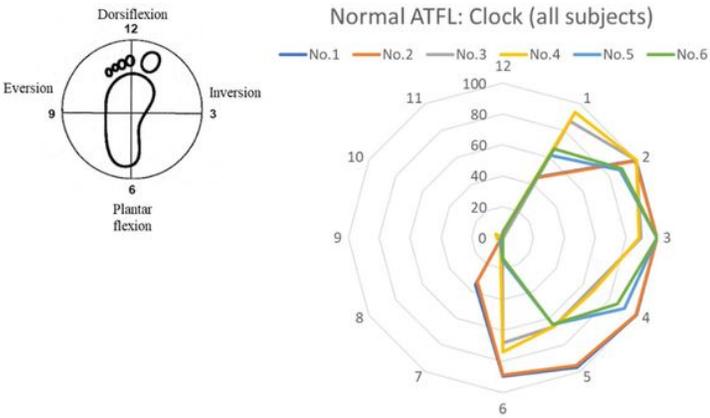
8A



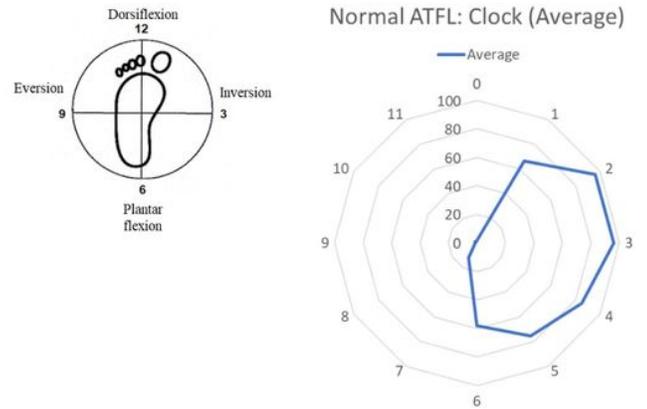
8B

Figure 8

The strain pattern of the anterior talofibular ligament at each end point in all specimens on the motion from 15° dorsiflexion to 30° plantar flexion. (A) All specimens. (B) Average.



9A



9B

Figure 9

The tensile pattern of the anterior talofibular ligament at each end point in all specimens on the clock. (A) All specimens. (B) Average.