

# The miniaturization ligament performance probe (MLPP) system for the three-dimensional analysis of ligament strain patterns throughout ankle motion

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## Research article

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# Abstract

## Background

Measuring strain patterns of joint ligaments in various positions informs our understanding their function. However, studies on the biomechanical properties of ankle ligaments are few, and the tensile properties of each ligament during motion have not been described because existing biomechanical sensors are too big to insert within the ankle. This study aimed to verify the validity of a novel miniaturized ligament performance probe (MLPP) system for measuring the strain pattern of the anterior talofibular ligament (ATFL) during ankle motion.

## Methods

The system is composed of a strain gauge (force probe), amplifier unit, display unit, and 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 tensile force, a round metal disk (clock; 150 mm in diameter), 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 ATFL strain at each end point detected by the miniature force probe.

## Results

Throughout motion required to shift from 15° dorsiflexion to 30° plantar flexion, the ATFL tensed near 20° plantar flexion, and strain increased as the plantar flexion angle increased. The ATFL was maximally tensioned at 3 and 4 o'clock in the inversion position. In the elastic range in which the ATFL is capable of returning to its original shape and length, tensile force was proportional to strain in all cases.

## Conclusion

The MLPP system could be used to effectively determine the relationship between limb position and small ankle ligament strain patterns.

## Background

Measuring strain patterns of joint ligaments in several different positions is necessary to understand their function. The biomechanical properties of large joints have been defined 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 existing biomechanical sensors used in large joint research are too big to fit within ankle ligaments.

We previously used a custom-made ankle ligament testing device to directly measure the load on each ligament of the ankle [6]. The device used 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, their usefulness under other conditions is limited.

In this study, we developed a novel miniaturized ligament performance probe (MLPP) that can be inserted into small ligaments to facilitate the measurement of ligament biomechanical properties. We aimed to verify the validity of MLPP anterior talofibular ligament (ATFL) strain pattern measurements during ankle motion.

## Methods

### *Structures of the MLPP system*

The MLPP system is composed of a strain gauge (force probe), amplifier unit, display unit, and logger (Figure 1). The system is capable of detecting small changes in resistance via a force probe. These changes in resistance are then enlarged by the bridge of the amplifier unit and then transferred to display unit output, where analog-to-digital conversion takes place. Subsequently, degree of strain is displayed. This strain measurement is then converted to an analog value, and its voltage is 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 that extend vertically on one side of its surface (Figure 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 within tissue, it may rotate as forces are applied, which may reduce or invert output (Figure 3A and B). To avoid this rotational influence, a tube for preventing rotation was attached to the force probe, and both ends were sutured to the target tissue (Figure 4).

A performance cube was used to measure the position of the ankle (Figure 5). The cube is composed of a nine-axis sensor (MPU-9250), microcontroller (ESP32), and logger. The MPU-9250 and ESP32 were loaded within the performance cube. The MPU-9250 is a sensor that records position information and measures 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 records data obtained from MPU-9250 and transmits it to the logger using a wireless module. The performance cube was synchronized with the MLPP system.

### *Cadaver source*

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). The 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 anatomy. All cadaveric studies were performed at the University of Barcelona in Catalonia, Spain. All methods in this study were reviewed and approved by the institutional review board of the same institution. 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.

### *Investigating AFTL strain patterns*

Procedures described in this section were performed on 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 placing the force probe into the ligament, the force probe tube was sutured to ligament fibers with a 3-0 nylon thread to prevent force probe rotation (Figure 4).

An Ilizarov ring-shaped external fixator was placed on the lower leg, and the lower limb was fixed vertically relative to the measurement desk using a vice to allow for the localization of distal upper and proximal lower portions of 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). The plate was fixed to the plantar aspect of the foot with a screw (diameter, 6 mm) and inserted into the calcaneus, and a rod (diameter, 8 mm) was inserted between the second and third metatarsals (Figure 5A). This plate had a 25-cm arm, and a 0.5-kg weight was added at its end, thus an approximate 1.2-Nm force was applied to the ankle and subtalar joint complex ( $0.5 \text{ kg} \times 0.25 \text{ m} \times 9.80665 = 1.23 \text{ Nm}$ ). The arm of the plate rotated every 30° on the clock and allowed for the measurement of AFTL strain each of its ends (Figure 5B). Dorsiflexion, plantar flexion, inversion and eversion ankle positions were designated when the plate arm was at the 12 o'clock, 6 o'clock position, 3 o'clock, and 9 o'clock position, respectively. The angles of axial motion, dorsiflexion, and plantar flexion were measured using an electronic goniometer (MPU-9250; TDK InvenSense), which was synchronized with the MLPP system. After all measurements were made in intact specimens, the ATFL was cut at fibular attachment points to free each force probe.

### *Data analysis*

The relationship between foot position and AFTL tensile force was analyzed. Tensile force data from the force probe were obtained by synchronizing the probe with the arm of the clock after each 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 was 0 and the maximum value was 100. The average values at each position were connected with a line, and the ligament tension patterns of specimens were compared.

## **Results**

Within the elastic range in which the ATFL is able to return to its original shape and length, tensile force was determined to be proportional to strain in all cases (Figure 6). The strain pattern of the ATFL at each end point in all specimens that underwent motion from 15° dorsiflexion to 30° plantar flexion is shown in Figure 7A and B and on the clock in Figure 8A and B. Throughout motion from 15° dorsiflexion to 30° plantar flexion, the ATFL tensed at around 20° plantar flexion, and 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 similar strain patterns, with axial and clock motion coefficients of variation of 0–1 and 0.05–1, respectively.

## Discussion

Our results showed that the MLPP system was effective in establishing the relationship between the limb position and AFTL ligament strain patterns. To gain a comprehensive understanding of the individual contribution of a ligament to overall ankle stability, an understanding of biomechanical properties of each individual ankle ligament is needed. By measuring ankle movement, we were able to assess the function of each ligament at a variety of limb positions using cadaver models. Results obtained by the MLPP system were similar to those that were determined using a different system [6]. The sensor used in the MLPP system is widely used in industry, and its accuracy is guaranteed. In addition, the insertion technique is simple, which facilitates the measurement of the strain pattern of the ATFL throughout ankle motion.

Previous studies, such as those that used Roentgen measurement [7], an Inman ankle machine [8], a magnetic position and orientation tracking system [9], a 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 ankle ligament biomechanical properties.

For the direct measurement of ligament load, the sensor should be inserted into the ligament. DeRouin et al. [13] reported the use of a system that employed a wireless sensor for measuring ligament tensile force in large joints. It had a high-force sensor that consisted of a stainless-steel strip with hooks at both ends. Although the system was able to directly measure load applied to the ligament, the size of the metal strip (28 × 1 × 0.5 mm) and the sensor (20 × 1 × 30 μm) was too big to be used in a small joint such as the ankle.

The previously developed custom-made ankle ligament testing device can directly measure each ligament's tensile pattern but custom-made [6]. This MLPP system made of available industrial products can be inserted into small ligaments, facilitating the precise measurement of AFTL strain patterns throughout ankle motion. We already confirmed the tension pattern of the deltoid ligament using this system [14]. Thus, the MLPP system will improve surgical repair precision and improve the reconstruction of ATFL injuries in the future.

## *Limitations*

A disadvantage of the MLPP is that it measures the strain value of the ligament instead of tensile force. In the elastic range in which the ATFL can return to its original shape and length, force and strain were linearly proportional. Therefore, it is theoretically possible to convert the strain value to newton-force if Young's modulus is obtained via calibration. However, it is difficult to accurately determine Young's modulus because the water content of the tissue decreases with time and ligament elasticity changes. The small degree of variation observed in this study may have been influenced by temporal changes in ligament elasticity.

## **Conclusion**

This study described a new MLPP system that effectively established the relationship between limb position and small ligament strain patterns in the ankle, thus enhancing our 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.

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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, YT wrote the first draft. RI critically reviewed the draft. All authors read and approved the final manuscript.

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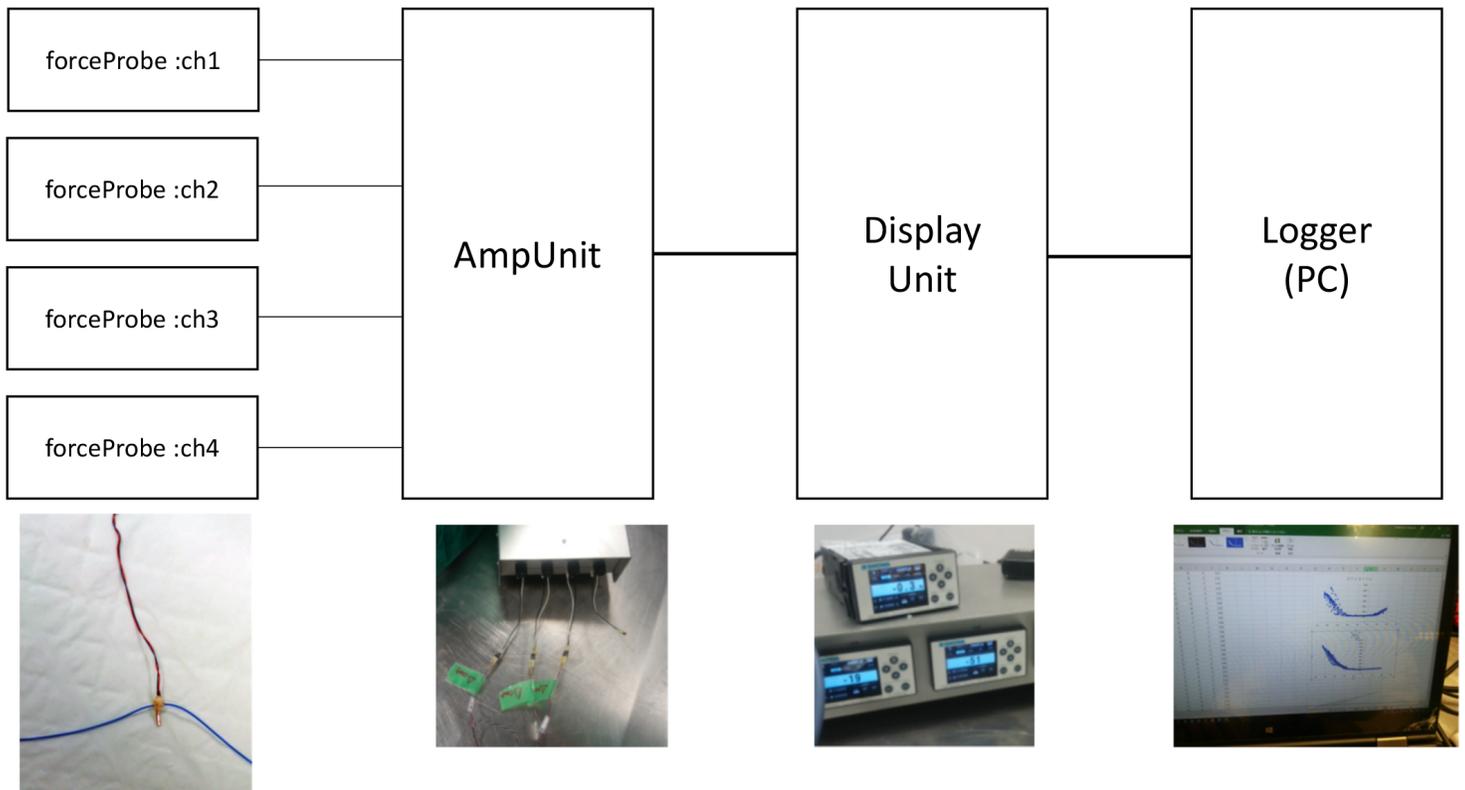
Not applicable.

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## Figures



**Figure 1**

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

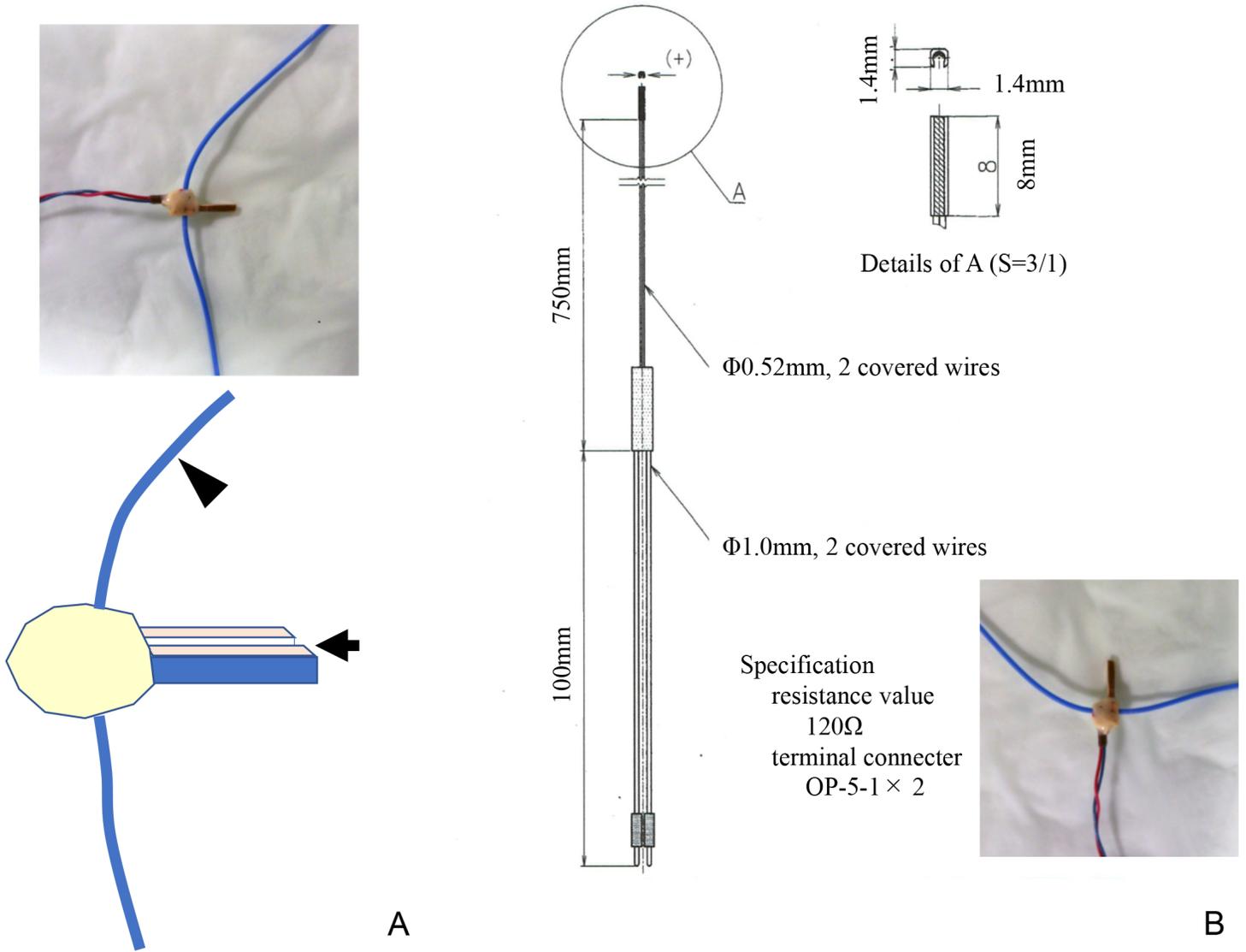


Figure 2

Force probe (strain gauge). A rectangular force probe (A) with a tubular structure that has slits that extend vertically on one side of its surface (B) is shown.

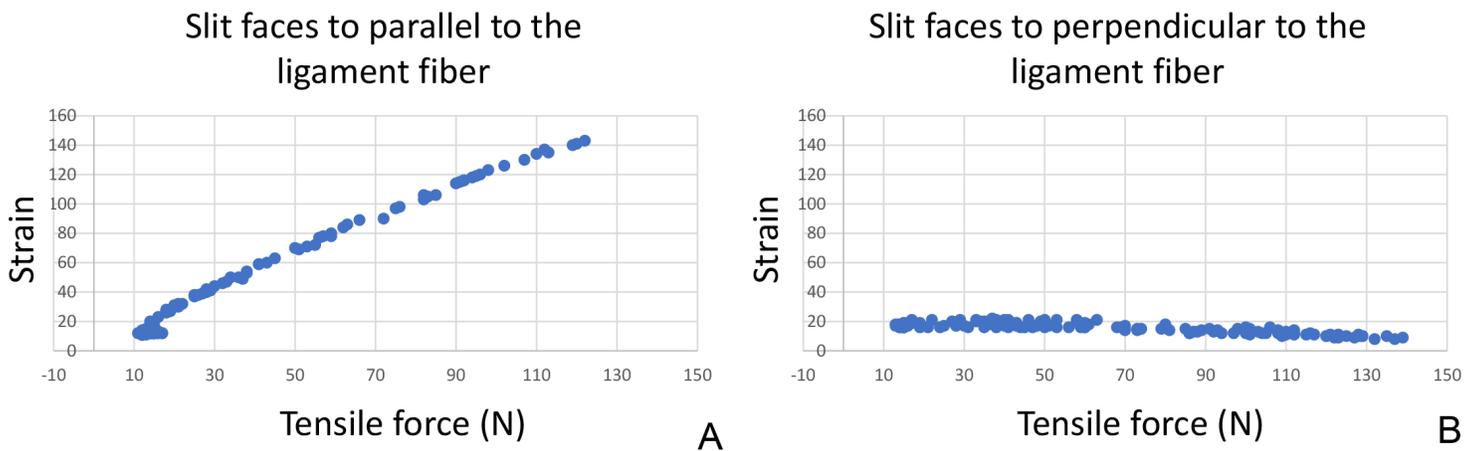
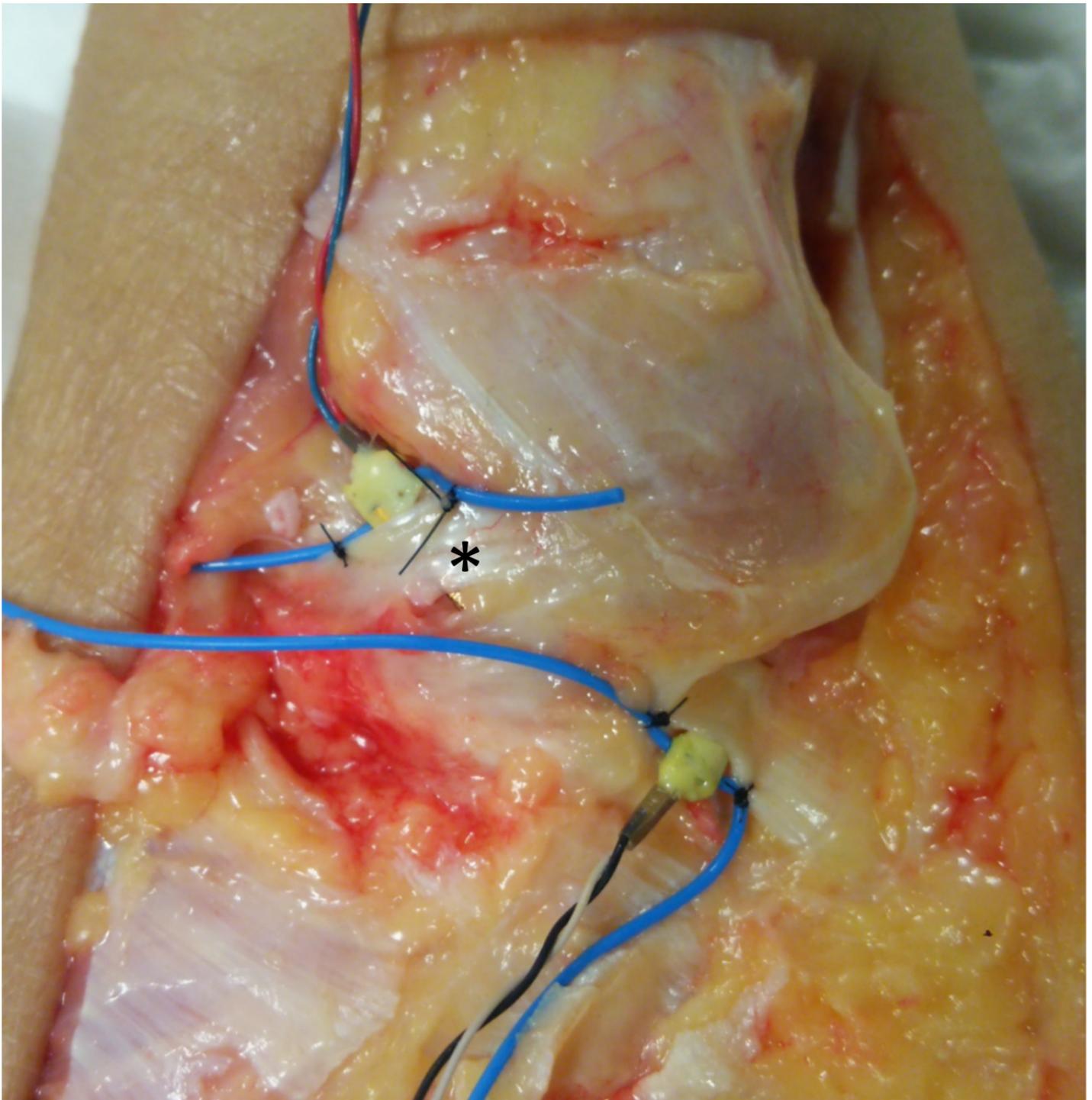


Figure 3

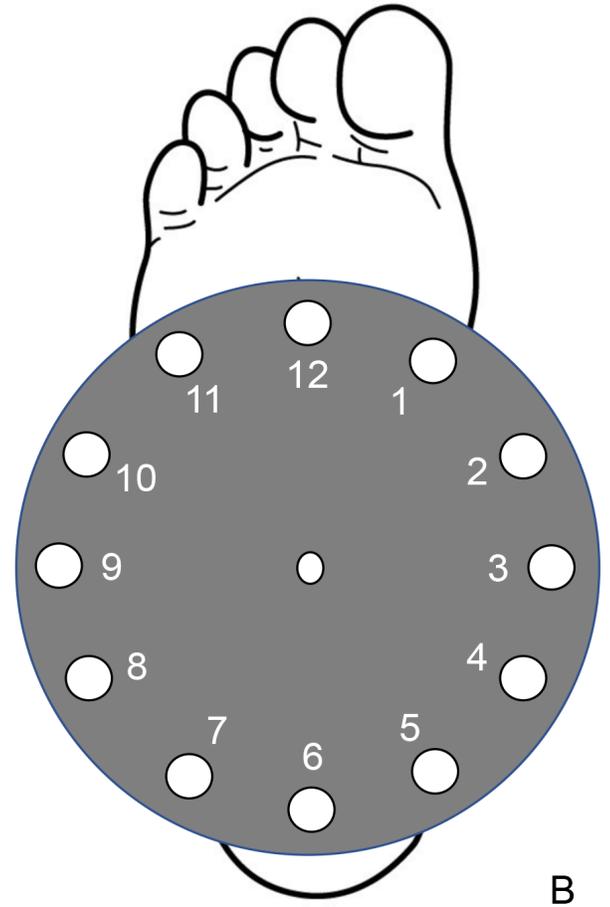
Differences in measured values that occur as a result of altered force probe slit angle. The ligament tensile pattern can be measured if the slit of the force probe is parallel to the ligament fiber as shown in (A). However, values will be skewed if the slit of the force probe is perpendicular to the ligament fiber, as shown in (B).



**Figure 4**

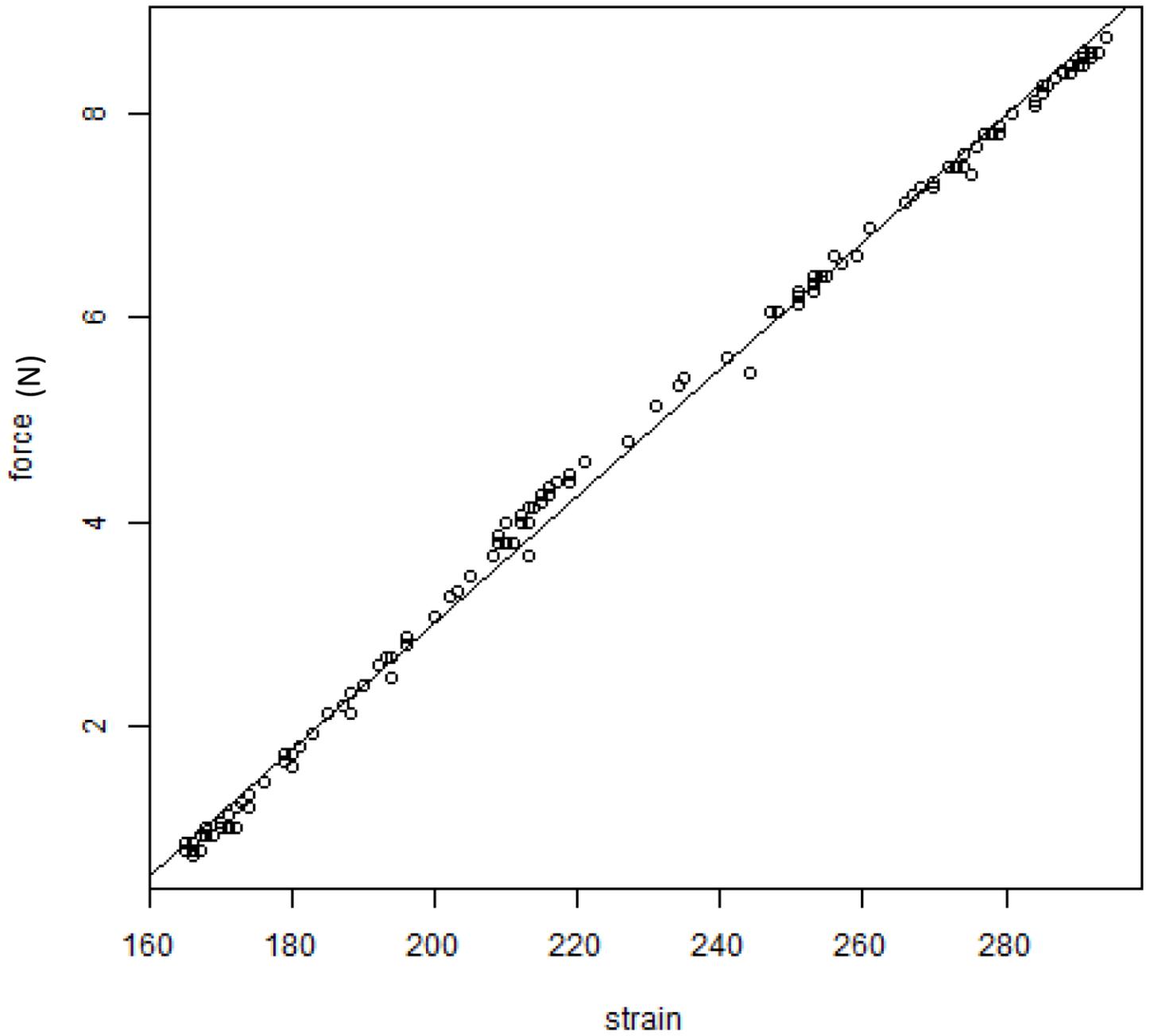
Insertion and fixation of the force probe into the anterior talofibular ligament. Both ends of the tube, which prevent rotation of the force probe in the ligament, were sutured to the anterior talofibular ligament

(\*).



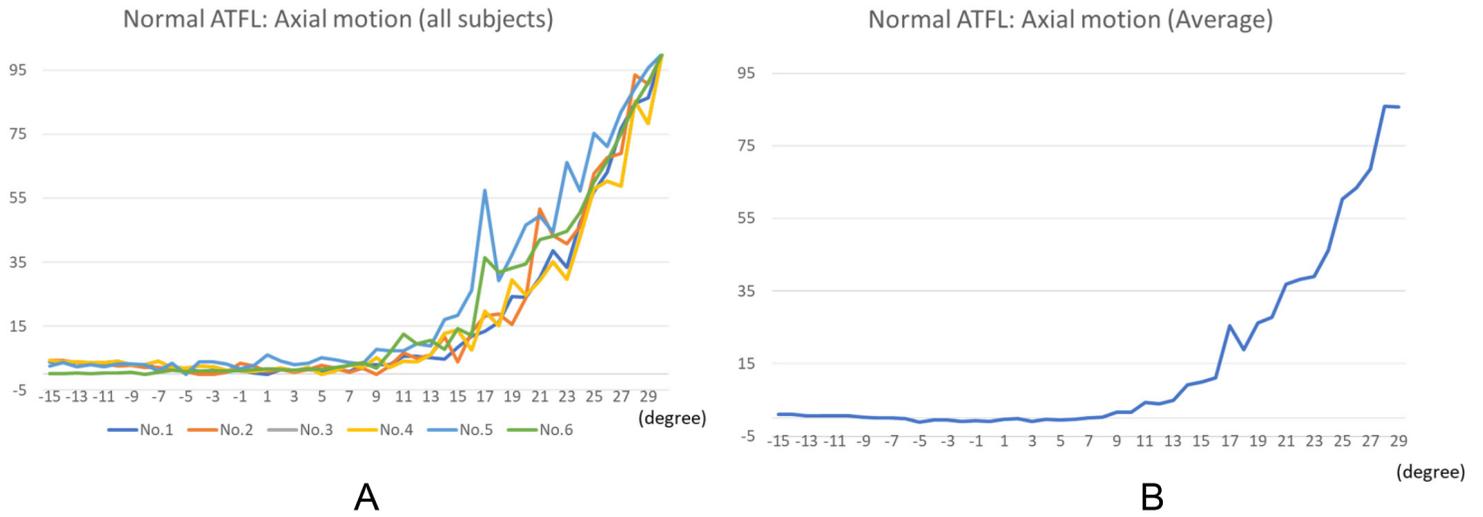
**Figure 5**

Specimen positioning. The lower limb, which was fixed vertically to the measurement desk using an Ilizarov ring-shaped external fixator, is shown (A). A clock (\*, B) and performance cube (†) affixed to an acrylic plate are shown.



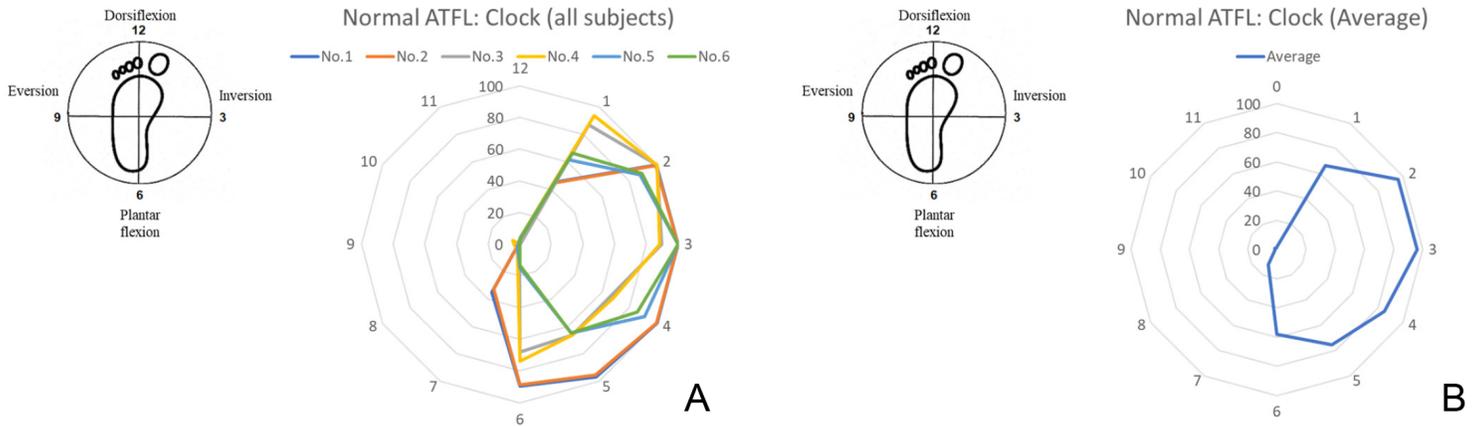
**Figure 6**

Tensile force data. Tensile force data collected from anterior talofibular ligament throughout ankle motion ranging from full dorsiflexion to full plantar flexion (10 times) is shown.



**Figure 7**

The strain pattern of the anterior talofibular ligament at each end point in all specimens throughout motion from 15° dorsiflexion to 30° plantar flexion. Individual values determined from (A) all specimens and (B) average values are shown.



**Figure 8**

The tensile pattern of the anterior talofibular ligament at each end on the clock. Tensile patterns of (A) all specimens and (B) average values are shown.