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ANKLE

Clinical failure after Dresden repair of mid-substance Achilles tendon rupture: human cadaveric testing

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Abstract
Purpose The purpose of this study was to describe the angle of clinical failure during cyclical mobilization exercises in the Achilles tendon of human cadaveric specimens that were repaired using the Dresden technique and FiberWire® No. 2. The secondary aim was to identify the secure limit of mobilization, the type of failure, and the type of apposition.
Methods The lower limbs of eight males (mean age: 60.3 ± 6.3 years) were repaired with the Dresden technique following complete, percutaneous mid-substance Achilles tendon rupture. A basal tension of 10 N at 30° of plantarflexion was placed on each specimen. The angle of the ankle during clinical failure (tendon ends separation >5 mm) was then tested via cyclical exercises (i.e. 100 cycles between 30° and 15° of plantarflexion; 100 cycles between 15° of plantarflexion and 0°; 100 cycles between 0° and 15° of dorsiflexion; and 100 cycles between 15° of dorsiflexion and full dorsiflexion). Clinical failure was determined using the Laplacian edge detection filter, and the angle of clinical failure was obtained using a rotatory potentiometer aligned in relation to the intermalleolar axis of each foot specimen. The type of failure (knot, tendon, or suture) and apposition (termino-terminal or non-termino-terminal) were determined. Descriptive statistics were used to obtain the mean; standard deviation; 95 % confidence interval; 1st, 25th, 50th, 75th, and 100th percentiles; and the standard error of the mean for angle data. Proportions were used to describe the type of failure and apposition.
Results The main results were a mean angle of clinical failure equal to 12.5° of plantarflexion, a limit of mobilization equal to 14.0° of plantarflexion, tendon failure type, and non-termino-terminal apposition in all specimens.
Conclusions While the mean angle of clinical failure in human cadaveric models was 12.5° of plantarflexion, after 14.0° of plantarflexion, the percutaneous Dresden technique was found insecure for cyclical mobilization exercises, with a 5 % range of error. These findings are clinically relevant as they provide mechanical limits for diminishing the risk of Achilles lengthening during immediate rehabilitation.

Keywords Achilles tendon · Dresden repair · Clinical failure · Mobilization exercises

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Introduction

Mid-substance Achilles tendon ruptures in men are increasing [10, 13] and have an incidence between 5.5 and 18 cases per 100,000 inhabitants each year [10, 16, 37]. This rupture directly compromises propulsion and landing tasks, such as

gait, running, and jumping [33, 35, 40]. To promote better outcomes after Achilles tenorrhaphy, repair designs have been recommended that offer appropriate mechanical stability during rehabilitation by providing better gapping resistance and greater ultimate tensile strength [10, 15, 19, 22, 26, 36].

Currently, immediate rehabilitation after Achilles tenorrhaphy [11, 16, 30, 36, 37, 39] is strongly supported [2, 4, 7, 11, 12, 14, 16, 18, 21, 38, 39] over traditional rehabilitation programs that include a prolonged period of initial rest [11, 16, 36, 37, 39]. Immediate rehabilitation programs begin exercise interventions from the inflammatory phase of tendon healing [9, 11, 16, 26, 34] to improve the strength of the repaired zone [9, 11, 16, 32, 34] and provide clinical and motor benefits [1, 3, 9, 10, 11, 14]. However, despite the benefits achieved by percutaneous tenorrhaphies in combination with immediate rehabilitation [5, 9], frequently, percutaneous techniques are not tested under cyclical models to determine values of critical tendon lengthening [5, 30]. Critical lengthening equal to 5 mm of separation between the tendon ends, also termed clinical failure [8, 26, 28], was established as the acceptable separation limit to protect the granular tissue during tendon healing [15, 22, 26, 27, 29, 30].

Concerning percutaneous tenorrhaphy [5], the Dresden technique preserves the paratenon after mid-substance Achilles tendon rupture to diminish post-operative comorbidity [1]. This technique is also quick and reproducible [5, 10, 19, 31], provides good clinical outcomes under traditional [10] and immediate rehabilitation models [9], and does not evidence increased complications as compared to other techniques [9, 11, 19, 39]. Additionally, the Dresden technique has withstood up to 328 N under pull-out testing [31], a resistance greater than that found for the Kessler and Krackow techniques [31]. However, this percutaneous technique was developed in experimental studies to control termino-terminal repair in an open approach, but as the assessed experimental conditions do not occur in a clinical context, it is still unknown if the Dresden technique can control termino-terminal repair and if this additional bias may promote early clinical failure.

Given these described limitations, it is important to determine the angle of clinical failure for dorsiflexion mobilization exercises so that mechanical limits can be properly adjusted to prevent clinical failure and secondary negative neuromuscular effects stemming from anatomical causes [35] following Achilles tendon repair with the Dresden technique. Therefore, the primary aim of this study was to describe the angle of clinical failure during cyclical mobilization exercises in the Achilles tendon of human cadaveric specimens that were repaired using the Dresden technique and FiberWire® No. 2. The secondary aim of this study was to identify the secure limit of mobilization, the type of failure (knot, tendon, or suture), and the type of apposition (termino-terminal or non-termino-terminal).

Materials and methods

Fresh-frozen human cadaveric specimens were used for experimental analyses. This study was performed at the Biomechanics Unit of the Instituto Traumatológico (Santiago, Chile) between August 2014 and April 2015, and was approved by the Institutional Review Board of the Instituto Traumatológico (Santiago, Chile) in accordance with Chilean Law 20,120 on Human Research, with the Declaration of Helsinki, and with regulations for cadaveric human research established by the Anatomy Laboratory of the Universidad de Chile (Santiago, Chile).

Specimen demographics

Experimental procedures were performed on lower limbs amputated from eight fresh-frozen male cadavers (mean age: 60.3 ± 6.3 years) obtained from the Anatomy Laboratory of the Universidad de Chile (Santiago, Chile). The specimens were stored at −20 °C and thawed 14 h before being manipulated in dissection and biomechanical tests.

All specimens were evaluated by three trauma surgeons (H.H., R.M., and S.R.) and one anatomist (M.S.) by ultrasonography and physical examination, and specimens were excluded from the study if there was any evidence of rearfoot or leg surgery, soft tissue pathology, excessive bony deformities, or any pathology of the plantar-flexor mechanism.

Mid-substance Achilles tendon rupture procedure

A partial percutaneous section was made on the Achilles tendon of each specimen with a No. 21 stainless steel surgical scalpel 5 cm from the central aspect of the calcaneal tuberosity identified by palpation (Fig. 1). Each incision was contiguously located at the lateral border of the Achilles tendon (Fig. 1c). Dorsiflexion was then used to rupture the Achilles tendon until a palpable gap was generated (Fig. 1d). To corroborate a complete disruption of the paratenon and longitudinal fibres of the Achilles tendon (Fig. 1e), the generated gap was assessed with a 7.5 MHz musculoskeletal ultrasound transducer (Sounmed Inc., Medley, FL, USA). This mixed model of Achilles rupture was performed to better approximate a clinical rupture of the tendon. All procedures needed to create a mid-substance rupture of Achilles tendon were performed by the same orthopaedic surgeon (H.H.).

Surgery procedure

After confirming the Achilles tendon rupture by ultrasonography, an orthopaedic surgeon (H.H.) performed percutaneous tenorrhaphy following the double-strand

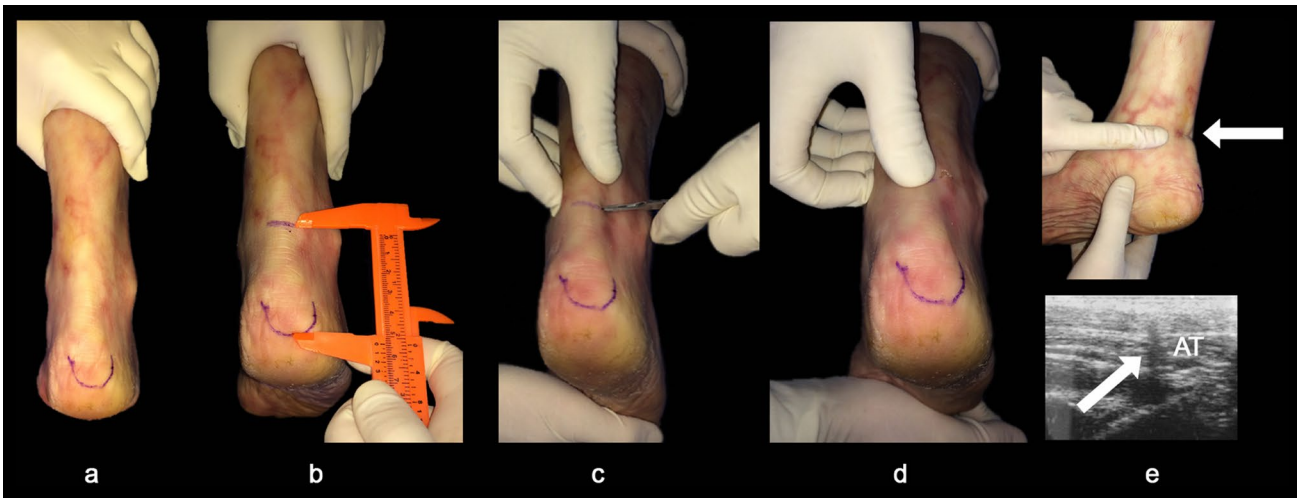

Fig. 1 Mid-substance Achilles rupture procedure. **a** Distal insertion of Achilles tendon; **b** mid-substance Achilles rupture zone at 5 cm; **c** Achilles tendon dissection; **d** gap palpation; and **e** confirmation of complete Achilles tendon rupture. *Top* clinical image, *Bottom* ultrasonography imaging

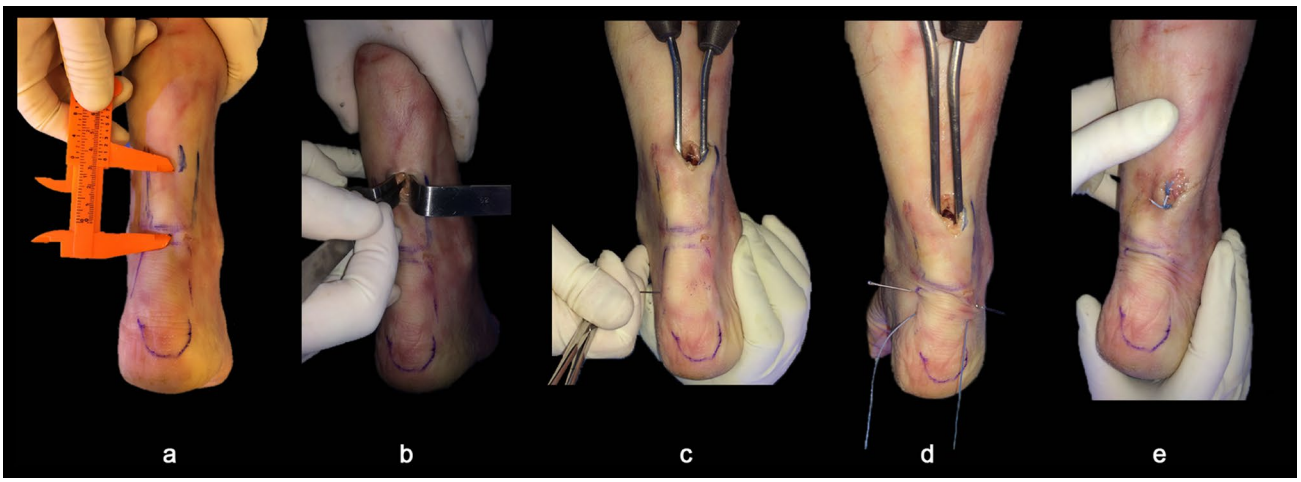

Fig. 2 Dresden technique. **a** Tendineus endings, gap, and posteromedial incision outlines; **b** opening of the crural fascia; **c** first thread; **d** second thread; and **e** suture traction used to achieve 20° of plantarflexion

Dresden technique [1] using FiberWire® Suture No. 2.0 (Arthrex Inc., Naples, Fl, USA), as summarized in Fig. 2. Before initiating surgical repair, the specimen was placed in a prone position, and the proximal portion of the triceps surae was fixed by a compress clamp to simulate proximal muscle insertion. First, the gap was identified by palpation (sensitivity of 0.73 and specificity of 0.89) [23], and the proximal and distal ends of the Achilles tendon rupture were outlined on the skin (Fig. 2a). Then, a 2-cm-long minimally invasive posteromedial incision was made 3 cm above the proximal end of the tendon rupture. Special care was taken to preserve the paratenon by performing an aperture between the superficial fascia and Achilles paratenon (Fig. 2b).

Through the aperture, two Dresden instruments [1] were positioned at the lateral and medial borders of the distal tendon end, approximately 1.5 cm from the calcaneal tuberosity border (Fig. 2c). The first suture was passed distally from the medial to the lateral plane through the distal inner diameter of the Dresden instruments. A second suture was passed parallel to and 1 cm proximal to the first suture, from the medial to lateral plane though the proximal inner diameter of the Dresden instruments (Fig. 2d). Then, the instruments were pulled proximally until the suture ends appeared by the posteromedial incision. To check that the distal sutures were firmly placed, the medial and lateral sutures were pulled until achieving full ankle plantarflexion. The sutures were strained with a tension necessary to

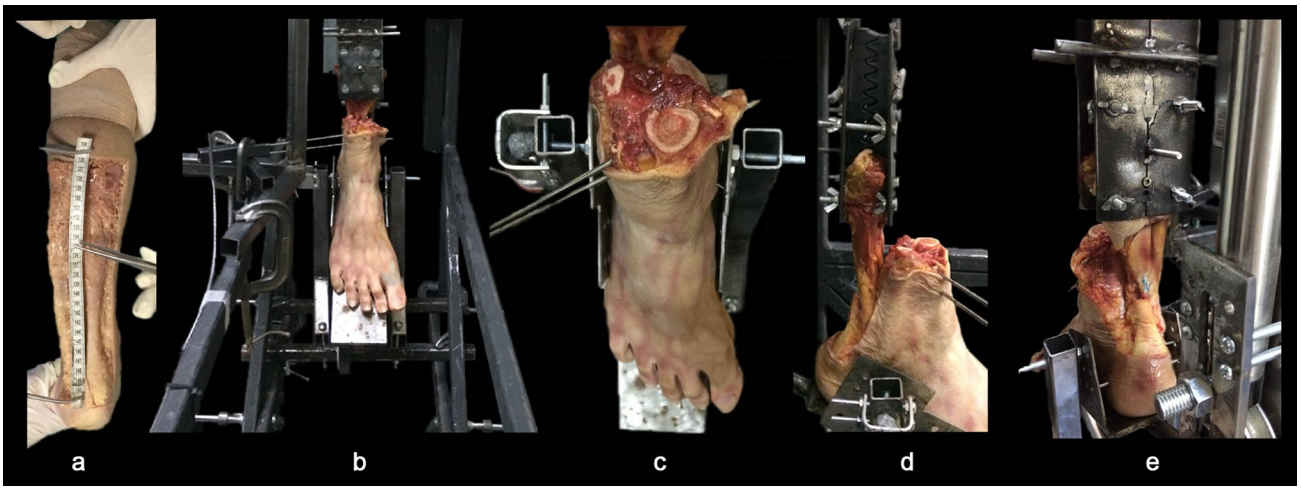

Fig. 3 Mounting of specimens. **a** Skin dissection; **b** frontal fixation; **c** transverse fixation; **d** sagittal fixation; and **e** Achilles tendon clamping

achieve 20° of plantarflexion and were tied with three simple knots.

To simulate the physiological equinus rest position of the ankle in the absence of a contralateral foot, 20° of plantarflexion was used [17]. This equinus position was recently described by Carmont et al. [6] as relevant due to the tenodesis effect, where it is essential to recover this physiological feature after Achilles rupture. To control the 20° of plantarflexion, a second trauma surgeon (R.M.) provided visual feedback of the position angle to the first surgeon (H.H.) who measured the plantarflexion angle by goniometry [1], employing the head of the fibula, the lateral malleolus, and the fifth head of the metatarsal as anatomical references to perform the pull-out of sutures and knots. To finalize the surgery, tenorrhaphy tendon continuity of the repair was checked by palpation to verify the absence of a gap [23].

Prior to biomechanical testing, the second surgeon dissected the skin and subcutaneous tissue of each specimen to expose the Achilles tendon and tenorrhaphy area (Fig. 3a). Each specimen was then amputated 10 cm from the fibular tip with a micro-oscillating saw (Inbioel, Argentina). The bone and soft tissue were resected, while muscle of the gastrocnemius tissue was kept.

Biomechanical testing

Before performing cyclical tests, the specimens were fixed to a steel plate that had one degree of freedom, thereby allowing sagittal movements of the ankle. This steel plate was attached by the base to a rigid custom-designed electromechanical system (Fig. 3b, c), based on the mechanical model described by Labib et al. [20]. The intermalleolar axis of each foot was oriented in relation to the mechanical axis of the steel plate (Fig. 3b, c). To achieve alignment between the intermalleolar axis and the mechanical axis of the steel plate during dynamic testing, each specimen had two fixation points from the steel plate to the lateral aspect of the calcaneus bone: one fixation point from the steel plate to the medial aspect of the body of the talus and two parallel fixation points from the mechanical device to the third portion of the tibia. To fix the calcaneus and talus, 3.0-mm stainless steel Kirschner wire was used, while 4.8-mm stainless steel Steinmann pins were used for the tibia. The Kirschner wire was cut with a saw to allow free rotatory movement of the steel plate in relation to the mechanical device. The fibula was left unattached to not restrict movement between the talus and fibula during dorsiflexion.

Then, the gastrocnemius and Achilles tendon were clamped (Fig. 3d, e), placing a basal tension of 10 N on the Achilles tendon of each specimen to simulate the maximum possible tension with the knee extended at 0° and at 30° of plantarflexion, according to the report by Davis et al. [8]. Finally, ten preload cycles were performed on each Achilles tendon specimen to complete initial tissue conditioning before cyclical testing [20].

Biomechanical testing consisted in a progressive, cyclical dorsiflexion mobilization model with a mechanical mobilization window of 15° of dorsiflexion that involved 400 repetitions structured into four progressive exercises.

The mobilization window was established to detect clinical failure when the tensile gap strength was equal to zero, such as occurs during the inflammatory phase [27, 29]. The selection of this phase was based on the findings of Kangas et al. [15], Mortensen et al. [27], and Nystrom et al. [29], where the critical separation of tendon ends occurred during this phase. Meanwhile, the selection of a mobilization range equal to 15° of dorsiflexion was based on the previous clinical experience of De la Fuente et al. [9], who set a value of −15° of dorsiflexion (15° of plantarflexion) during

the inflammatory phase in patients treated with the double-strand Dresden technique in combination with immediate rehabilitation. The range was also based on previous in vitro cyclical loads that simulated an early rehabilitation in bovine specimens, where a window of 15° induced linear tendon elongation equal to 11.7 mm under a traction velocity of 6 mm/s. This tendon elongation was sufficient to cause clinical failure in bovine Achilles tendons repaired with the double-strand Dresden technique. Considering these prior observations, it is relevant to determine if this quantity of mobilization can induce clinical failure in human specimens.

The mobilization assessments were structured into four progressive exercises to identify the angle of dorsiflexion [20] at which clinical failure occurred (tendon end separations >5 mm). The first exercise had 100 cycles between 30° and 15° of plantarflexion; the second, 100 cycles between 15° of plantarflexion and 0°; the third, 100 cycles between 0° and 15° of dorsiflexion; and the fourth, 100 cycles between 15° of dorsiflexion and full dorsiflexion. Cyclical testing used a maximum exercise repetition of 400, as established by standard practice limits used by the Instituto Traumatológico (Santiago, Chile) during the first 2 weeks of rehabilitation. This model design was able to determine clinical failure within a range of 30° of plantarflexion to full dorsiflexion in each specimen, a range in which clinical failure was expected to occur. This design was also used to create an isolated mechanical environment for early mobilization exercises.

The cyclical mobilizations and the tensions placed on the Achilles tendon were executed using a custom electromechanical system (Fig. 3b) controlled by MATLAB 2010a (Mathworks Inc., USA). This electromechanical system had a direct 7 kN current linear actuator (Linear Actuator World, China) (Fig. 3e) to induce dorsiflexion at 6 mm per second [25] and an S-beam load-cell transducer (Revere Transducer Inc., USA) attached to the Achilles tendon using a compressor clamp (Fig. 3a, d, e) to acquire samples of the signal at 1000 Hz. On the lateral aspect of the mechanical axis of the steel plate, a rotatory pontentiometry of 10 K (Fig. 3b) was attached to acquire signal samples at 1000 Hz. The shaft of the potentiometer was fixed to the mechanical device, and the metal casin was fixed to the mobile steel plate to record the relative angle between the fixed position of the device and the change in the angle of the steel plate where the specimens were fixed. The tenorrhaphy area (tendon ends) was also recorded by two 1 megapixel digital cameras (Fujitel Limited Partnership, Thailand), with signal samples acquired at 30 Hz.

Precision and accuracy

The precision of the mobilization measurements was ±0.04°, and the mean accuracy was $r = 0.96$. The accuracy was assessed by a test–retest assay performed before the cadaveric assessments. Test–retest assessments were carried out over 2 days at 24-h intervals and were performed by configuring footplate mobilization for 30° to 15° of plantarflexion ($r = 0.95$, $n = 2000$ samples), 15° of plantarflexion to 0° ($r = 0.96$, $n = 2000$ samples), 0° to 15° of dorsiflexion ($r = 0.97$, $n = 2000$ samples), and 15° to 30° of dorsiflexion ($r = 0.95$, $n = 2000$ samples). The correlation coefficient against an analogue inclinometer (precision equal to ±1°) was $r = 0.92$ ($n = 8000$ samples).

The precision of gap measurements was ±0.1 mm, and the accuracy was $r = 0.94$. The accuracy was assessed by test–retest assays in 100 samples over 2 days at 24-h intervals and by displacing the clamp ends by 5 mm. The correlation coefficient against the analogue metric rule (precision equal to ±1.0 mm) was $r = 0.94$.

Outcomes

The angle of clinical failure was recorded when tendon ends reached a separation greater than 5 mm, in accordance with the definitions of Lee et al. [22] and Orishimo et al. [30]. The separation of tendon ends was detected using a Laplacian edge filter, where $\nabla^2 f$ was the Laplacian operator used to create the edge filter, such as described in Eq. (1). In MATLAB 2010a (Mathworks Inc., USA), a kernel with the generic form of $(f(x-1,y-1)\,f(x-1,y)\,f(x-1,y+1); f(x,y-1)\,f(x,y)\,f(x,y+1); f(x+1,y-1)\,f(x+1,y)\,f(x+1,y-1))$ was used. To obtain the filtered image, two-dimensional convolution was performed in an iterative frame-to-frame mode between the original image and the kernel using the "valid method" for the convolution. When a frame had a central distance equal to 5 mm, the angle of the potentiometer signal was detected as the angle of clinical failure.

$$\nabla^2 f = \partial^2 f/\partial^2 x + \partial^2 f/\partial^2 y. \quad (1)$$

The limit of mobilization was calculated as the lower limit of the 95 % confidence interval of the angle of clinical failure.

The type of failure was obtained by visual inspection after the cyclical tests. Knot failure was defined if there was an insufficient knot; tendon failure if there was a tear at any suture point, and suture failure if any strands ruptured.

The type of apposition was obtained by visual inspection before the cyclical tests, where termino-terminal apposition was determined if the Achilles tendon ends were adjacent and where non-termino-terminal apposition was determined if termino-terminal apposition did not exist before the cyclical tests.

Statistical analysis

Descriptive statistics were used to obtain the mean; standard deviation; 95 % confidence interval; 0, 25, 50, 75, and

100 percentiles; and the standard error of the mean for angle data. Proportions were used for statistical descriptions of the type of failure and apposition. All statistical calculations were performed using the STATA 12 software (STATA Corp Lp., Texas, USA). Finally, the sample size was obtained through the non-probability haphazard sampling method and using only the samples available to the Anatomy Laboratory of the Universidad de Chile (Santiago, Chile).

Results

The angle of clinical failure had a mean of 12.52° of plantarflexion; standard deviation of ±6.78°; 95 % confidence interval of 14.04° to 10.81° of plantarflexion; 1st percentile of 20.86° of plantarflexion; 25th percentile of 18.50° plantarflexion; 50th percentile of 11.49° plantarflexion; 75th percentile of 6.84° of plantarflexion; 100th percentile of 4.38° of plantarflexion; and a standard error of the mean of ±2.39°. The limit of mobilization was 14.04° of plantarflexion. Tendon failure was 100 % (8/8), and suture and knot failures were not observed. The type of apposition was 100 % (8/8) for non-termino-terminal apposition, while termino-terminal apposition was not observed.

Discussion

The most important finding of the present study was that percutaneous Dresden tenorrhaphy presented clinical failure at 14.0° of plantarflexion. Since the angle at clinical failure was previously unknown for cyclical mobilization exercises during immediate rehabilitation after mid-substance Achilles tendon tenorrhaphy with a percutaneous approach, the present study assessed this parameter through experimental biomechanical testing on fresh-frozen human cadaveric Achilles tendon specimens repaired with the Dresden technique [1, 9, 10]. This study represents the first report on mechanical parameters for therapeutic exercises in early rehabilitation models following percutaneous repair of the Achilles tendon.

The current results suggest that double-strand Dresden tenorrhaphy, as originally described by Amlang et al. [1], is secure for mobilization exercises under 14.0° of plantarflexion. Additionally, special care must be adopted for this technique, with a strict control of the mobilization range for exercises during rehabilitation, in accordance with incidences of early tendon end separations found by Nystrom et al. [29], Mortensen et al. [26], and Kangas et al. [15] as a result of tensile deformation during the first 2 weeks after tendon repair.

The present results, obtained in fresh-frozen human cadaveric specimens, suggest that clinical failure occurred due to cyclical tensile deformations that create tears in the suture-tendon interface (i.e. support points). This pattern of tendon failure was found in 100 % (8/8) of the examined specimens. It is possible that the Dresden technique using FiberWire® No. 2 created a concentrated stress point in the cadaveric Achilles tendon, thus causing an axial cut effect at the support sites. Without plastic deformation of the strands, or due to insufficient knots, this effect would exclusively increase tendon separation and promote clinical failure. Considering these observations, it is of relevance to control mobilization during rehabilitation following intervention with the double-strand Dresden technique, and this control could be achieved by using an articulated boot while exercising or by any restrictor device together with clear indications to patients. However, to diminish the stress at the four support points and to mechanically optimize the design of the double-strand Dresden technique, it may be possible to add a third strand similar to that used in the Achillon repair design [5].

The present results also support that early clinical failure, with a limit of 14.0° of plantarflexion, can occur even with a relatively low number of exercise repetitions, i.e. lower than 400 repetitions. This is clinically relevant as it supports the possibility of promoting early lengthening of the Achilles tendon with few repetitions if an incorrect range of mobilization is used. Importantly, physical therapists and physicians could feel a false sense of security when working under zero degrees of dorsiflexion and with low repetitions.

Despite abundant evidence for the effectiveness of early rehabilitation programs [2–4, 7, 9, 11, 12, 14, 16, 21, 24, 33, 38, 39], there is a lack of guidance in the literature regarding the appropriate mechanical limits for therapeutic exercises during the first weeks of rehabilitation following tenorrhaphy. Additionally, the re-rupture rate has been the principal focus for assessing the effectiveness of early rehabilitation [16, 39]. However, lengthening is the main deleterious effect during early rehabilitation that does not result in a re-rupture [22, 30, 33]. Tendon end separation greater than 5 mm [22] during the healing process may promote a longer final length of the muscle–tendon unit in the plantar-flexor mechanism [33]. This lengthening has been associated with pathological neuromuscular adaptations to compensate for deficiency in the plantar-flexor mechanism during the heel raise test [33] and during gait [35]. This supports that more basic scientific investigations are needed to optimize post-operative treatments and to prevent pathological neuromuscular adaptations resulting from anatomical causes [35].

On the other hand, the specimens repaired in the present study did not achieve termino-terminal apposition despite

reproducing the percutaneous approach described by Amlang et al. [1] and as achieved by open approaches [31]. Instead, overlapping tendons were found in each repaired specimen, causing an oblique orientation of the strands and a lower factor of resistance that was equal to the resistance per sin of strand inclinations by trigonometric assumption. It is possible that the strands might have been excessively pulled out during suturing, a step performed to achieve a physiological plantar position of rest, causing a silent overlapping of tendon ends for the Dresden technique. However, new human cadaveric models of research are needed to determine the mechanical effectiveness of tendon overlapping employing percutaneous approaches.

The limitations of this study include that the mechanical model of the repair zone was constant. In reality, the tensile strength of the repaired zone will increase over the course of rehabilitation. Furthermore, this model is only applicable to mobilization exercises when the interface between ends is considered without elastic properties (tensile strength equal zero). Also, a new mechanical model is needed to determine weight-bearing limits during early rehabilitation. Finally, this study only assessed one kind of percutaneous repair, and future studies need to determine the mechanical efficiency of other techniques in an immediate rehabilitation model.

This study is clinically relevant in that it provides mechanical parameters for physicians and physical therapists for adjusting therapeutic mobilization exercises during the first weeks of early rehabilitation following Dresden tenorrhaphy, thereby contributing towards the prevention of tendon lengthening.

Conclusions

The mean angle of clinical failure was 12.5° of plantarflexion. However, after 14.0° of plantarflexion, the percutaneous Dresden technique was found insecure for cyclical mobilization exercises. Therefore, if mobilization exercises are used during rehabilitation following Dresden tenorrhaphy, these should only be performed within a protective range between full plantarflexion and 14.0° of plantarflexion.

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Authors' contributions C.D. generated the research idea, participated in the experimental design, biomechanical assessments, data analysis, general study coordination, and drafting the manuscript. G.C. participated in biomechanical assessments, general study coordination, and drafting the manuscript. M.S. participated in anatomical interventions, general study coordination, and drafting the manuscript. H.M. participated in the experimental design, data analysis, general study coordination, and drafting the manuscript. H.H. participated in the experimental design, surgical interventions, biomechanical assessments, and drafting the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

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