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Biomechanical properties of different techniques used in vitro for suturing mid-substance Achilles tendon ruptures

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ABSTRACT

Background: The Dresden technique preserves the paratenon during Achilles tendon repair and may improve the plantarflexor mechanism when combined with mobilization during early rehabilitation. However, the surgical repair design for Achilles tendon ruptures can affect rates of re-rupture or lengthening. Therefore, the aim of this study was to determine the biomechanical properties of the Krackow, Double-Kessler, Double-Dresden, and Triple-Dresden techniques used for repairing mid-substance Achilles tendon ruptures during cyclical and maximum traction.

Methods: Sixty mid-substance bovine tendons repaired after transverse rupturing were divided randomly into four groups by repair technique: Krackow, Double-Kessler, Double-Dresden, and Triple-Dresden. Cyclical tractions of 4.7, 5.8, 7.9, and 11.7 mm (equivalent to 5°, 8°, 10°, and 15° of dorsal flexion, respectively) were applied to determine gapping, tensile strength, nominal suture stress, repair deformation, and specimens with clinical failure (gap > 5 mm). Maximal traction was applied to measure maximum strength and failure type (i.e. suture, knot, or tendon).

Findings: The Triple-Dresden technique resulted in decreased gapping, nominal suture stress, repair deformation, and quantity of specimens with clinical failure as compared to the other techniques. Furthermore, Triple-Dresden tendons showed greater comparative tensile and maximum strength. During maximal traction testing, this technique presented tendon failure, whereas the Krackow, Double-Kessler, and Double-Dresden techniques had suture failures.

Interpretation: Triple-Dresden repair results in better cyclical and maximum traction strengths, suggesting that this technique might be more appropriate when performing early mobilization after mid-substance Achilles tendon rupture repair.

1. Introduction

Mid-substance rupturing of the Achilles tendon frequently occurs in active adult males (De la Fuente et al., 2016a; Longo et al., 2012). This incidence is increasing and is between 5.5 and 9.9 for North America and 2.1 and 21.5% cases per 100,000 inhabitants in Nordic countries (Lantto et al., 2015; Suchak et al., 2005). Early post-operative mobilization leads to better clinical outcomes as it improves muscular-tendinous tropism, angiogenesis, and collagen distribution in the direction of the traction, in addition to preventing peritendinous adhesions (Pneumaticos et al., 2000; Palmes et al., 2002; Ahn and Choy, 2011; Kearney et al., 2012). However, early mobilization interventions may result in excessive tendon traction, and increase the risk of a re-rupture (Ortiz et al., 2012) and tendon lengthening (De la Fuente et al., 2017; Silbernagel et al., 2012; Suydam et al., 2015).

Re-rupture and tendon elongation have devastating effects on the force-length relationship of the plantar flexors (Suydam et al., 2015). The post-operative stage is fundamental to promote an adequate force-length relationship by early improvements in plantar flexion force, and medial gastrocnemius mechanics (De la Fuente et al., 2016b) or

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Fig. 1. Specimen dissection and mid-substance injury mechanism: the white arrow shows the midsubtance rupture of the Achilles tendon, and the black arrow shows the suture employed for repair. A) Localization of rupture on Achilles tendon, 4.5 cm proximal to its calcaneal insertion. B) The simulated Achilles tendon rupture.

adequate deep and superficial plantar flexion synergies (Finni et al., 2006). However, there is no consensus about which surgical technique is the best to provide resistance during early rehabilitation where these changes could be favored. The degree of risk for re-rupture and tendon lengthening depends on the prevention of clinical failure (i.e. tendon end separation > 5 mm), which is influenced by the repair design (De la Fuente et al., 2017; Orishimo et al., 2008; Ortiz et al., 2012; Sadoghi et al., 2012). Standard surgical designs include the Krackow and Kessler techniques, which involve open-surgery tissue dissection and expansion before repair (Sadoghi et al., 2012). The Krackow technique uses a closed loop design on the lateral borders of tendon endings to attach the strands and brings the tendon ends closer until complete apposition by tightening and tying the free strands (McCoy and Haddad, 2010). In turn, the Kessler technique achieves complete tendon end apposition by tightening and tying the free strands to obtain complete intratendinous apposition (Dinopoulos et al., 2000). Percutaneous techniques are generally preferred over open surgeries due to presenting fewer complications, e.g. wound breakdown and infection, and favoring tendon cicatrization (Taglialavoro et al., 2011).

Percutaneous procedures, such as the Dresden technique (Amlang et al., 2006; Kakiuchi, 1995), preserve the paratenon and improve tendon healing. The Dresden technique results in lower tensile strength since it produces an inclination of the strands (De la Fuente et al., 2017), as modeled by the equation $||\text{Maximal suture strength} * e^{j\theta}||_2$. Therefore, strand strength could be increased by using a collinear technique in the transverse plane to minimize the cosine component, which can be achieved by adding a new strand (Keller et al., 2014), thereby optimizing maximal suture strength. The abilities of existing Achilles tendon surgical techniques to prevent clinical failure in early rehabilitation programs are scarce and tested under maximal traction. However, there is a lack of evaluations under conditions of cyclical traction. Therefore, it is unknown if the Dresden technique produces better results with the triple or double configuration. Additionally, the differences produced by the Dresden technique as compared to traditional techniques during cyclical and maximal traction are unclear.

In this study we determine the biomechanical properties of the Krackow, Double-Kessler, Double-Dresden, and Triple-Dresden techniques used for repairing mid-substance Achilles tendon ruptures during cyclical and maximum traction. Our null-hypothesis was that the Triple-Dresden repair technique does not improve biomechanical properties (e.g. gapping, tensile strength, suture nominal stress, and repair deformation) during cyclical traction and does not result in the highest tensile strength during maximal traction as compared to the Krackow, Double-Kessler, and Double-Dresden techniques.

2. Methods

2.1. Study design

A simple randomized comparative experimental study design was conducted. First, numbers were randomly assigned to the tendon specimens (n = 60). The tendons were then evenly divided among the four surgical technique groups (i.e. Krackow, Double-Kessler, Double-Dresden, and Triple-Dresden). The specimens were stored at −18 °C until experimental assessments. Prior to surgery and biomechanical testing, each specimen was gradually thawed and kept hydrated for 12 h at room temperature (≈ 18 °C). After experimentation, the tendon specimens were eliminated according to waste disposal guidelines for biological material. All procedures were conducted with approval of the local institution according to the 1986 European Community Council Directive 86/609/EEC for the protection of animals used for scientific purposes.

2.2. Specimen demographics

Specimens were obtained from a local slaughterhouse according to national regulation No. 19,162. For assays, 60 fresh two-year-old Achilles tendons of bovines were included (Fig. 1A). Two medical doctors inspected the specimens to ensure that no tendon pathologies were present. Table 1 summarizes the demographic characteristics of the samples.

Table 1
Baseline dimensions of Achilles tendons by groups.

Dimension	Surgical group			
	Krackow (n = 15)	Double-Kessler (n = 15)	Double-Dresden (n = 15)	Triple-Dresden (n = 15)
AP diameter, mm	8.00 (1.05)	8.30 (1.16)	9.80 (1.62)	7.50 (1.43)
Lateral diameter, mm	10.00 (1.33)	9.70 (1.42)	9.30 (1.25)	9.00 (1.41)
Cross section, mm^2	63.35 (14.85)	63.90 (16.60)	71.04 (11.34)	53.14 (13.05)[a]

Data are presented as mean (standard deviation).

[a] This value differs significantly from those in the other groups at the 0.05 level.

AP = Anteroposterior.

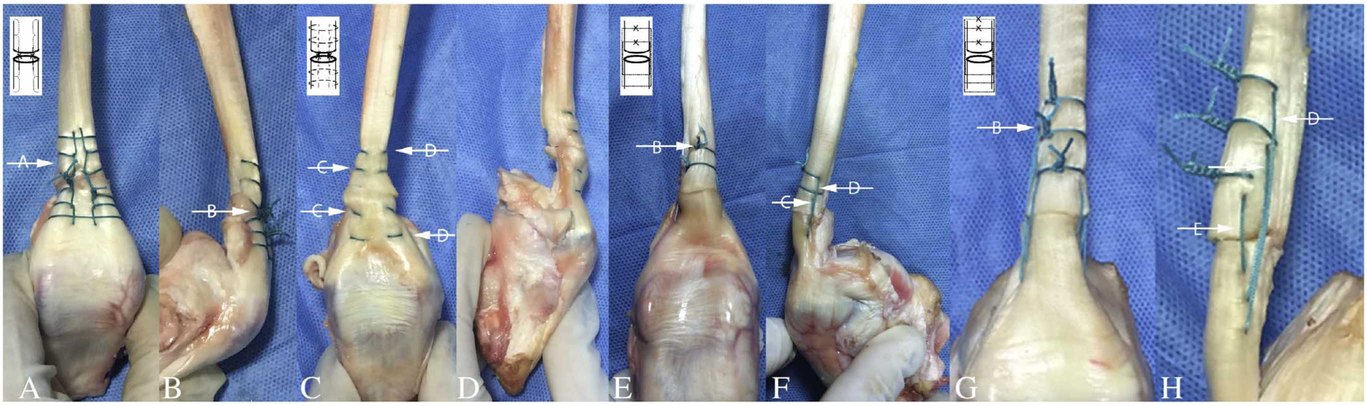

Fig. 2. Achilles tendon repair techniques: white arrow A shows the closed attaching loop used for Krackow repair; white arrow B shows the knots; white arrow C shows the first suture; white arrow D shows the second suture; and white arrow E shows the third suture. A) Frontal view of Krackow repair. B) Lateral view of Krackow repair. C) Frontal view of Double-Kessler repair. D) Lateral view of Double-Kessler repair. E) Frontal view of the Double-Dresden repair. F) Lateral view of Double-Dresden repair: G) Frontal view of Triple-Dresden repair. H) Lateral view of Triple-Dresden repair.

2.3. *Surgical procedure*

An orthopedic foot and ankle surgeon carried out all surgical procedures. To begin, each specimen was transected to expose the Achilles tendon (Fig. 1A). Achilles tendon rupturing was then caused by using a No. 21 scalpel to sever the mid-substance 4.5 cm from the calcaneal insertion, through a section running perpendicular to the tendon fibers (Fig. 1B). To compare the mechanical designs of repairs each tendon was subsequently repaired using the Krackow, Double-Kessler, Double-Dresden, or Triple-Dresden techniques with No. 2 polyester braided non-absorbable suture (Ethibond Excel™, Ethicon Endo-Surgery, Inc., Somerville, USA).

The Krackow technique was performed according to Krackow (2008). Three locking loops were placed 1 cm from either side and at each end of the rupture (Fig. 2A). The loops were tightened to obtain end-to-end repair and were tied with one double and five simple knots (Fig. 2B). The Double-Kessler technique was performed using Pennington's modification by adding a second suture (Sebastin et al., 2013). The first and second sutures were positioned 1.0 cm and 1.5 cm, respectively, from either side of the rupture (Fig. 2C). The sutures were also tightened to obtain end-to-end repair, and then tied with one double and five simple knots (Fig. 2D). The Dresden technique was performed as described by Amlang et al. (2006), with sutures from the central lower third of the tendon to the central upper third. For the Double-Dresden technique, the first and second sutures were placed 1.0 cm and 1.5 cm, respectively, from either side of the rupture (Fig. 2F). The sutures were tightened to obtain end-to-end repair and then tied with one double and five simple knots (Fig. 2E). For the Triple-Dresden technique (Fig. 2G and F), a third suture was added 0.5 cm from either side of the rupture (Fig. 2H).

2.4. *Biomechanical testing*

Each repaired specimen was mounted on a testing machine (Fig. 3A) configured to exert cyclical or maximum traction, as controlled by custom programming in the Matlab v7.1 software (Mathworks Inc., Massachusetts, USA). A 7 kN electric linear actuator (Linear Actuators World, Ningbo, China; Fig. 3A) was attached to a compressive clamp (Fig. 3A) at the proximal end of each specimen (Fig. 3B). The bone end was fixed by a Steinmann pin drilled from the lateral-to-medial aspects (Fig. 3C). Each Steinmann pin was clamped into place with two external orthopedic fixations (Fig. 3A) attached to a custom fixed base plate (Fig. 3A). Two digital cameras recorded the experiments at a sampling rate of 30 Hz.

Tendon traction during early mobilization was simulated according to the standardized protocol from the Instituto Traumatológico (Santiago, Chile), a national center of traumatic diseases. This rehabilitation protocol is used in patients during the first 14 days after mid-substance Achilles tendon repair. It includes 100 dorsiflexion mobilizations per session, performed twice a week. Consequently, the simulated protocol involved four sets of 100 tractions if clinical failure (gap tendon ends $>$ 5 mm) did not occur, or if it occurred at the end of 400 cyclical tractions. Three sets of 100 tractions were performed if clinical failure occurred at the end of 300 cyclical tractions. Two sets of 100 tractions were performed if clinical failure occurred at the end of 200 cyclical tractions. One set of 100 tractions was performed if clinical failure occurred at the end of 100 cyclical tractions. Since the level of traction (i.e. mobilization) during rehabilitation is unknown, the effects of four different lengthening exercises were explored. These exercises stretched the specimen using displacement control mode through linear potentiometer integrated in the linear actuator by 4.7 mm after the first 100 traction sets, 5.8 mm after the second 100 traction set, 7.9 mm after the third 100 traction set, and 11.7 mm after the fourth 100 traction set. These stretches represent four different degrees of mobility that represent 5°, 8°, 10°, and 15° of dorsal flexion according to the equations described by Davis et al. (1999). Dorsal flexion movements were defined from the joint position in which the Achilles tendon had zero Newton of tension. After the cyclical traction, the maximum traction was induced by cumulative loading until failure (Fig. 3C–F).

2.5. *Data acquisition and processing*

Force signals were sampled at 1000 Hz by an S-Beam load cell (#9363, Revere Transducer Inc., California, USA). The range of the instrument was 0 to 500 kgf, with resolution of 0.0375 kgf and sensitivity of 3 mV/V. The signal was digitally converted by a 14-bit A/D converter (USB-OEM card #6009, National Instrument Corp., Austin, TX, USA) and treated with a finite, second-order 10 Hz low-pass Butterworth impulse response filter using the Matlab v7.1 software (Mathworks Inc., Massachusetts, USA).

RGB images were recorded at 30 Hz by two 8-megapixel digital cameras (Fujitel Limited Partnership, Bangkok, Thailand). The frames were detected every 0.13 mm of linear displacement by the linear actuator. Pixels were linearly transformed to distance by calibrating a reference frame using a known initial distance attached over the longitudinal axis of each specimen, which was positioned perpendicular to the camera lens. Images were modified by converting RGB images to gray-scale images standardized by 255, obtaining pixels between 0 and 1, where 0 was black and 1 was white. Tendon end separation was directly measured at the suture axis using the Matlab v7.1 software (Mathworks Inc., Massachusetts, USA).

Fig. 3. Experimental set-up. A) Custom traction machine: white arrow A indicates the load cell device employed; white arrow B indicates the linear actuator; white arrow C indicates the compressive clamp; and white arrow D indicates the fixation site for the distal end of specimens. B) Compressive clamp at the tendon end. C) Krackow group specimen after biomechanical testing: white arrow E indicates suture rupture. D) Double-Kessler group specimen. E) Double-Dresden group specimen: white arrow G indicates the first suture rupture, and white arrow J indicates non-rupture of the second suture, generating a distal tear at the tendon end. F) Triple-Dresden group specimen: white arrow J indicates a tear pattern after biomechanical tests.

2.6. *Outcomes*

The baseline characteristics measured for the rupture area of each specimen were anteroposterior diameter, lateral diameter, and cross-sectional area estimated by ellipsoidal approximation (π × major diameter × minor diameter × 0.25). Seven outcome variables were tested: 1) gapping (distance between the tendon ends along the repair axis), 2) tensile strength (maximum force withstood during cyclical traction after repair), 3) nominal suture stress (tensile strength × the number of sutures^{-1}), 4) repair deformation (percent change between the final and initial repair lengths, as measured from the inferior clamp border and the superior Steinmann border), 5) the number of specimens with clinical failure (gap > 5 mm), 6) maximum strength (maximum force obtained after maximal traction and before the complete repair rupture), and 7) type of failure (most frequent pattern of failure [e.g. suture, knot, or tendon] after the maximal traction).

2.7. *Statistical analysis*

Data were reported as the mean and standard deviation. The Shapiro-Wilk test was used to confirm the normality of data distribution. Homoscedasticity was confirmed using Levene's test, and the assumption of equal variances between all possible group pairs was confirmed by Mauchly's test. Gapping, tensile strength, nominal suture stress, repair deformation, and maximal resistance were compared between surgical techniques using a repeated-measured analysis of variance with Bonferroni's correction for multiple comparisons. When a *p* value for the F statistic was lower than 0.05, Bonferroni's post-hoc test was applied to detect the mean difference between groups. Data were analyzed using the STATA 12 software (STATA Corp. LP, Texas, USA).

3. Results

Group baselines were similar ($p > 0.05$), except for the tendon cross-section in the Triple-Dresden group, which was significantly smaller compared to the other three groups (Table 1). The Triple-Dresden group had the lowest gapping, nominal suture stress, repair deformation, and number of specimens with clinical failure as compared to the other techniques. Furthermore, the Triple-Dresden group presented the greatest tensile and maximum strengths among the assessed techniques. The type of failure observed after maximal traction was tendon for the Triple-Dresden group, and suture for the Krackow, Double-Kessler, and Double-Dresden groups (Tables 2 and 3).

Table 2
Effect of cyclical traction.

Variable	Surgical group			
	Krackow (n = 15)	Double-Kessler (n = 15)	Double-Dresden (n = 15)	Triple-Dresden (n = 15)
Gapping, mm				
5°	4.46 (1.36)^{a,b,d}	3.26 (1.48)^{c,d}	2.67 (1.43)^{c,d}	0.40 (0.90)^{a,b,c}
8°	6.00 (0.00)^{d}	5.21 (0.80)^{a,d}	4.07 (1.55)^{b,d}	1.55 (1.47)^{a,b,c}
10°	–	–	4.63 (1.96)^{d}	2.44 (1.66)^{a}
15°	–	–	7.00 (0.00)	4.77 (1.34)
Tensile strength, N				
5°	37.28 (11.87)^{b,d}	49.05 (13.93)^{c,d}	44.64 (23.45)^{d}	62.69 (19.42)^{a,b,c}
8°	51.30 (5.59)^{a,d}	77.70 (18.64)^{d}	76.13 (27.37)^{d}	107.62 (19.33)^{a,b,c}
10°	–	–	97.90 (42.28)^{d}	144.21 (26.98)^{a}
15°	–	–	174.62 (0.00)^{d}	266.44 (40.12)^{a}
Nominal suture stress, N/mm^2				
5°	81.11 (25.79)^{a,b,d}	53.29 (15.10)^{c}	48.57 (24.85)^{c}	44.44 (14.15)^{c}
8°	111.43 (12.21)	84.41 (20.23)	79.77 (20.24)	76.97 (13.85)
10°	–	–	106.10 (21.16)	104.52 (19.52)
15°	–	–	189.80 (0.00)	193.07 (19.10)
Repair deformation, %				
5°	3.09 (2.17)^{a,b,d}	1.62 (1.66)^{c}	1.45 (1.33)^{c}	1.75 (1.23)^{c}
8°	8.80 (4.58)^{a,b,d}	2.91 (1.59)^{c}	3.87 (2.68)^{c}	3.43 (1.54)^{c}
10°	–	–	12.80 (2.18)^{d}	5.50 (2.11)^{a}
15°	–	–	17.33 (0.00)^{d}	8.41 (2.42)^{a}
Specimens with clinical failure, %				
5°	12/15 (80)	5/15 (33)	3/15 (20)	0/15 (0)
8°	3/15 (20)	10/15 (66)	6/15 (40)	1/15 (6)
10°	–	–	5/15 (33)	1/15 (6)
15°	–	–	1/15 (6)	9/15 (60)

N = Newtons, mm = millimeter, % = percentage.
Data are presented as mean (standard deviation).
Percentage data are presented with truncate method.
[a] Differs significantly from the Double-Dresden techniques at the 0.05 level.
[b] Differs significantly from the Double-Kessler techniques at the 0.05 level.
[c] Differs significantly from the Krackow techniques at the 0.05 level.
[d] Differs significantly from the Triple-Dresden techniques at the 0.05 level.

4. Discussion

The most important finding in our study is that the Triple-Dresden repair results in lower gapping, fewer specimens with clinical failure, decreased repair deformation, less nominal stress to the suture (until 10°), and the highest tensile strength during cyclical and maximal

Table 3
Effect of maximal traction.

Variable	Surgical group			
	Krackow (n = 15)	Double-Kessler (n = 15)	Double-Dresden (n = 15)	Triple-Dresden (n = 15)
Maximum strength, mean (SD), N	94.5 (11.0)[a,d,b]	154.6 (15.6)[a,c,d]	245.4 (51.4)[b,c,d]	421.5 (45.1)[a,b,c]
Type of failure, mode, %	Suture 14/15 (93)	Suture 15/15 (100)	Suture 8/15 (53)	Tendon 8/15 (53)

N = Newtons.
Data are presented as mean (standard deviation).
Percentage data are presented with truncate method.
[a] Differs significantly from the Double-Dresden techniques at the 0.05 level.
[b] Differs significantly from the Double-Kessler techniques at the 0.05 level.
[c] Differs significantly from the Krackow techniques at the 0.05 level.
[d] Differs significantly from the Triple-Dresden techniques at the 0.05 level.

tractions as compared to the Double-Dresden, Double-Kessler, and Krackow techniques. Furthermore, after maximal traction the Triple-Dresden repair failed due to tendon tearing being classified as tendon type of failure. These findings indicate that Triple-Dresden repair is the most appropriate technique for tendon repair following Achilles tendon rupturing, especially when coupled with early mobilization rehabilitation, but under excessive traction could create lengthening by tendon tearing.

The lower gapping obtained using controlled electromechanical loads is consistent with the previously reported for maximum traction results (Ortiz et al., 2012). Moreover, the Triple-Dresden technique produced the lowest number of specimens with clinical failure, which was interpreted as the range of motion at 10° during dorsal flexion. More specifically, only 2 of the 15 specimens failed, with a further 9 specimens failing at reaching 15°. The Triple-Dresden technique produced a larger range of motion after repair when compared to the Double-Dresden and Krackow techniques, which suggest that the Triple-Dresden technique is better at preventing gap generation, a situation that often reduces healing quality (Lee et al., 2008) and affects the length of the muscle-tendon plantar flexor unit (De la Fuente et al., 2017; Suydam et al., 2015). Unfortunately, tendon lengthening can negatively affect the force-length relationship and increase the risk of re-rupture. Therefore, lengthening must be prevented during early rehabilitation (De la Fuente et al., 2017; Silbernagel et al., 2012; Suydam et al., 2015).

Additionally, at 15° the nominal stress to Triple-Dresden sutures increased with low deformation, suggesting that this technique would be prone to clinical failure resulting from tendon tearing. The type of failure recorded during maximal strength testing supports this hypothesis (Fig. 3F). In contrast, increased repair deformation for the Double-Dresden, Double-Kessler, and Krackow techniques was related to increased suture failure (Table 3). The Triple-Dresden technique might concentrate stress at the tendon-suture interface during progressive gap generation. It seems to occur at high traction levels due the capacity of the Triple-Dresden technique to sustain the stress over suture under values of ruptures, in contrast to the double configuration of Dresden technique, which achieve the failure rupture point of sutures. In this regard, the Triple-Dresden technique may induce non-uniform load distribution over the tendon under traction load, where the suture and tendon are in contact, such as observed in other corporal structures (Ma et al., 2014). At the distal tendon end, the suture runs horizontally (perpendicularly orientated in respect to axial axis of tendon end) changing to vertical direction (parallel in respect to axial axis of tendon end) at corner, and this geometrical configuration promotes an increased compressive force at this zone, which could create a cut effect that alters the tendon macrostructure. We hypothesize that the local rupture of corners could be the cause of the pathological tendon elongation after an early rehabilitation. Altogether, local tendon tearing and subsequent sub-clinical Achilles lengthening could occur in combination with rigid suture materials; a poor-quality and low-rigidity tendon, as could occur in pathological tendons; and excessive traction generated during a wrong rehabilitation. However, this mechanical phenomenon and their statistical factor of interaction must be studied with a new experimental design.

The greater tensile and maximum strengths obtained by using the Triple-Dresden technique suggest that the number of sutures through the tendon ends could be essential for preventing clinical failure during early rehabilitation. The Triple-Dresden technique uses three times more stitches than the Krackow technique, and two times more than the Double-Dresden and Double-Kessler techniques. Indeed, the Triple-Dresden technique shows strong geometrical similarity to the percutaneous tendon technique Achillion (Longo et al., 2012; Sadoghi et al., 2012). Increased strength capacity against traction was also observed in the study of hand flexor tendons, where the surgical technique and the number of sutures between tendon ends were essential factors for increasing tensile strength (Dinopoulos et al., 2000). However, it is possible that using the Dresden technique does not provide the collinearity and symmetry needed to minimize the cosine component of strands. Minimizing the cosine results in greater tensile and maximum strengths by mathematical assumptions i.e. vectorial decomposition (Beer et al., 2012). When applied percutaneously, the Dresden technique produces a strand inclination (i.e. existence of a cosine component) that could probably be prevented by using an open approach; unfortunately the open approach has negative effect on the tissue. Therefore, a non-collinear technique and an asymmetrical load on sutures, as caused by an unbalanced technique, are the major mechanical limitations of the Dresden techniques.

Finally, our research is limited by factors such as conducting experiments in bovine specimens, the implemented tracking methods and, the mechanical models used. The angular results should be analyzed with caution. Furthermore, our model started from a baseline tension of zero Newton, according to Davis et al. (1999). Future research is needed to determine these parameters in human models. Altogether, the present and future studies will help in establishing limits for different surgical techniques during early rehabilitation, thus providing the means to differentiate between methods based on gait, mobilization, and the combination of these.

5. Conclusions

Triple-Dresden repair provides the best biomechanical results during cyclical traction (i.e. less gapping, higher tensile strength, lower suture nominal stress and, reduced repair deformation) and the highest tensile strength during maximal traction compared to the Krackow, Double-Kessler, and Double-Dresden techniques when repairing mid-substance Achilles tendon ruptures.

Conflict of interests

The authors declare no conflicts of interest.

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