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The elastic capacity of a tendon-repair construct influences the force necessary to induce gapping

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Abstract

Purpose Most biomechanical investigations of tendon repairs were based on output measures from hydraulic loading machines, therefore, accounting for construct failure rather than true gapping within the rupture zone. It was hypothesized that the elastic capacity of a tendon-repair construct influences the force necessary to induce gapping.

Methods A tendon-repair model was created in 48 porcine lower hind limbs, which were allocated to three fixation techniques: (1) Krackow, (2) transosseous and (3) anchor fixation. Loading was performed based on a standardized phased load-to-failure protocol using a servohydraulic mechanical testing system MTS (Zwick Roell, Ulm, Germany). Rupture-zone dehiscence was measured with an external motion capture device. Factors influencing dehiscence formation was determined using a linear regression model and adjustment performed as necessary. A 3-mm gap was considered clinically relevant. Analysis of variance (ANOVA) was used for comparison between groups.

Results The elastic capacity of a tendon-repair construct influences the force necessary to induce gapping of 3 mm (F_{3mm}) [$\beta = 0.6$, confidence interval (CI) 0.4–1.0, $p < 0.001$]. Furthermore, the three methods of fixation did not differ significantly in terms of maximum force to failure (n.s) or F_{3mm} (n.s).

Conclusion The main finding of this study demonstrated that the higher the elastic capacity of a tendon-repair construct, the higher the force necessary to induce clinically relevant gapping.

Level of evidence Controlled biomechanical study.

Keywords Achilles · Rupture · Tear · Krackow stitch · Anchor fixation · Transosseous fixation · Gap · Gapping · Dehiscence · Elongation · Elasticity · Repair · Tendon · PONTOS · Force · Failure

Introduction

Injuries of energy transferring ligaments and tendons represent a hallmark entity in the orthopaedics field. The significant disability resulting from insufficient energy transfer to bone propels these injuries to occupy a large volume of surgical orthopaedic practice [7, 16, 19].

The aim of any surgical treatment is to restore the functional integrity of the tendon or ligament to recover the loading capacity and optimize energy transfer [7, 17]. A stable fixation, preventing gap formation by withstanding forces during the early rehabilitation period should be aimed for [2].

Despite the presence of a diversity of surgical fixation techniques, the reality is that there is no true consensus in that regard, making that choice based on surgeon preference [7, 9, 18, 22].

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The majority of published biomechanical reports are based on comparison between available fixation methods [3, 4, 8, 11, 14, 18]. These studies commonly rely on construct failure as an endpoint and displacement measures produced by mechanical testing systems (MTS). Since displacement produced by the loading cell—MTS arms—is likely to be partially transferred to the tendon before gapping occurs, it would be fair to emphasize the need for consideration of the role of the tendon as well as the tendon-fixation interface on true gapping between the repaired tendon ends. Such studies would require external measurement of gapping. Although previously described, the application of external gap measurement devices was not commonly performed in biomechanical tendon repair studies [5, 13].

The aim of this study was to identify properties of a tendon-repair construct that show an influence on gapping using a multivariate linear regression model.

It was hypothesized that the higher the elastic capacity of a tendon-repair construct, the more force necessary to induce gapping between the repaired ends.

Materials and methods

Tendon preparation

The porcine tendon-repair model has previously been shown to be a reliable construct for biomechanical tendon studies [10, 13, 20].

In this study, the right-sided lower porcine hindlimb was used for the conduction of every experiment. All samples were obtained from one single slaughterhouse. Based on the dissections performed for this study, one of the anatomic variations of the porcine limb is that there is no common Achilles tendon. Both the gastrocnemius and solus tendons insert separately into the calcaneus in close proximity to each other, though separated by connective tissue. The soleus tendon being the more dominant of the two. Due to the short nature of the soleus tendon, the proximal tendinous portion of the digitorum superficialis (FDS) tendon, which crosses the calcaneus medially and has similar macroscopic characteristics to the soleus tendon, was also harvested. Thereby, two tendons were harvested for the conduction of each experiment.

Tendon-repair construct

Each tendon presented an arm in the tendon-repair construct, one being the soleus and the other being the FDS tendon. The tendon ends were transected to prepare for standardized repair. Three tendon repair techniques were applied: (1) Krackow suture, (2) transosseous suture and (3) anchor fixation. ORTHOCORD #2 sutures (Johnson & Johnson, New Jersey, USA) were used. All repair techniques involved the application of Krackow sutures to the proximal tendon. This was done by arming the proximal tendon with three throws bilaterally ending 4 cm proximal to the rupture, reinforced by a second row ending 3.5 cm proximally.

The distal fixation was performed as follows:

Group 1—Krackow repair was performed by applying sutures to the distal tendon, three throws bilaterally beginning 4 cm distal to the rupture and exiting in the rupture zone, reinforced by a second row starting 3.5 cm distally. The sutures were finally passed into the proximal tendon and proximal repair performed in a double row krackow technique as described above. Sutures were secured with five surgical knots in the proximal tendon.

Group 2—The distal bony fixation was performed by drilling a 3.2-mm transverse hole through the calcaneus through which two ORTHOCORD #2 sutures were passed. All ends were then passed through the substance of the distal tendon then the proximal tendon to throw double-rowed krackow sutures as described above. Sutures ends were secured with five knots.

Group 3—The distal bony fixation was performed by inserting an anchor (HEALIX BR™ anchor system, DePuy Mitek a Johnson & Johnson, New Jersy, USA) into the calcaneus, with two anchor sutures being passed through the distal substance of the tendon then proximal tendon to throw double-rowed krackow sutures as described above. Suture ends were each secured with five knots. Figure 1 shows a schematic illustration of each fixation method.

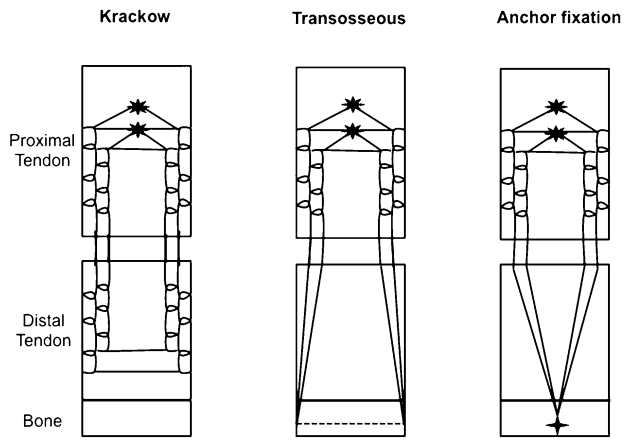

Fig. 1 Schematic illustration of each of the three fixation methods. All proximal repairs constituted krackow repair. The dotted line refers to the transosseous suture through the calcaneus. The star refers to a bone anchor in the calcaneus. The proximal buttons each represent five surgical throws

Installation of the tendon-repair construct

The calcaneus with soleus insertion was sliced in the coronal plane and freed from any ligamentous attachments, then attached to the distal unit of the servohydraulic mechanical testing system MTS. The proximal FDS tendon was fixed in a collinear fashion to the proximal unit comprising a threaded rod. The Zwick MTS with an XForce HP Type loading cell (Z 2.5 kN Zwick/Roell, Ulm, Germany) was used, with a position resolution of 0.027 µm and repetition accuracy of 2.0 µm.

For measurement of gapping between the tendon ends, the PONTOS 3D motion analysis (GOM, Braunschweig, Germany) system was used (Fig. 2). The PONTOS system is based on capturing 3D motion based on defined reference points. The measurement of the gap using the motion capture device allows for discrimination between tendon elongation and gap formation. The accuracy of the system was determined by calculating the mean difference between the displacement of the MTS machine arms and the corresponding optic measures of the PONTOS capture device, with a loaded tendon. The accuracy of the PONTOS system based on the mean of 10 repetitions was calculated to be 0.001 mm.

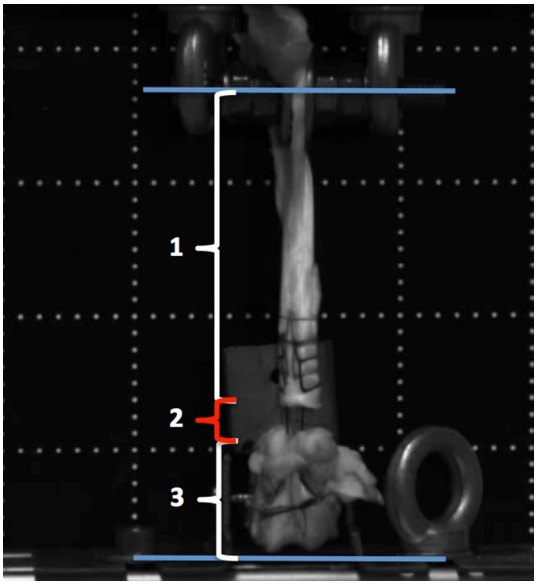

Fig. 2 A PONTOS 3D image illustrating the tendon-repair construct fixed within the mechanical testing machine. 1: Proximal portion of tendon (flexor digitorum superficialis FDS). 2: Dehiscence between the ruptured ends as captured by the PONTOS 3D camera. 3: The distal portion of the simulated rupture (soleus tendon)

Loading protocol

The loading protocol included four phases, which are illustrated in Table 1. The protocol was chosen based on previous pilot experiments, taking into account the position resolutions of both the MTS and PONTOS systems as well as the observation that 3-mm gapping occurs within the first 100 N of applied force. Failure was defined as a 20% loss of maximum force build-up F_{max} (Fig. 3).

Outcome measures

Six outcome parameters were defined and measured during every experimental cycle. These included:

1. Settling behaviour (%): the percentage change in force built-up during the second settling phase in the loading protocol.
2. Maximum force F_{max} (N): defined as the maximum force build-up within the tendon-repair construct before failure (defined as a 20% loss of maximum force build-up).
3. F_{3mm} (N): the force required to induce gapping of 3 mm between the tendon ends. The value of 3 mm was chosen based on previous studies indicating that 3 mm was the maximum threshold for ideal tendon healing [6].
4. Stiffness (N/mm): defined as the extent to which the tendon-repair construct can resist deformity by measuring the force per 1 mm of deformation.
5. Elastic construct capacity (%): defined as the percentage change in construct length just prior to occurrence of any gapping.
6. Elastic modulus (N/mm^2): defined as the stress/strain ratio of the tendon repair construct.

An institutional review board approval was not needed for this particular study design.

Table 1 Loading protocol

Force (N)	0–10	10	0–100	100–
Timeline	2 mm/s	15 s	0.2 mm/s	2 mm/s
Phase	One	Two	Three	Four

Phase 1: Baseline tensioning until the maximum tension of 10 N is reached. Phase 2: The force maintained to allow for settling of the tendon-fixation construct. Phase 3: The tension was steadily increased until a force of 100 N was achieved. Phase 4: Loading to failure was finally achieved by driving the machine at a steady rate until failure of the construct was reached. Failure was defined as a 20% loss of maximum achieved tension

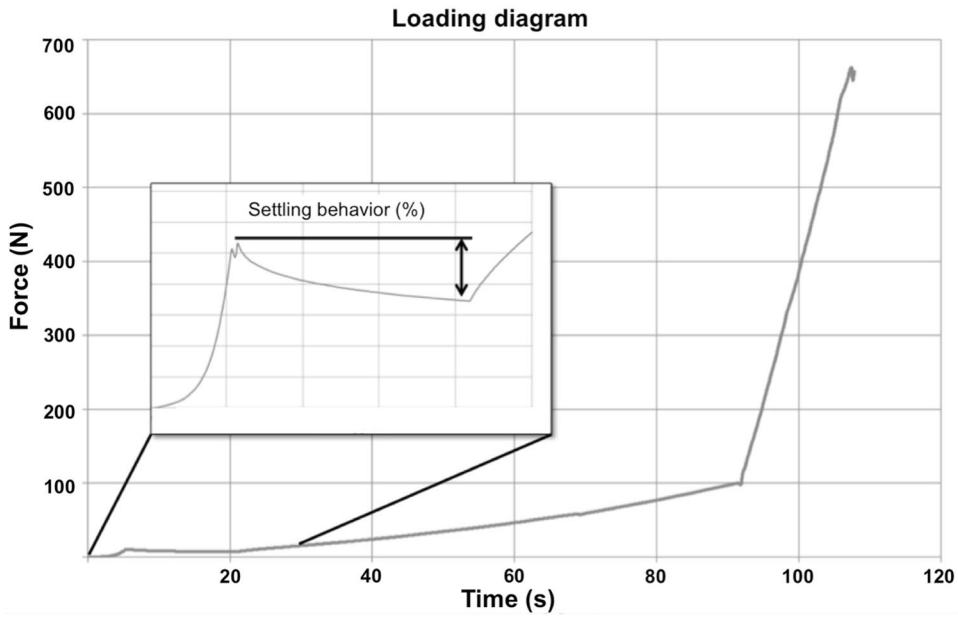

Fig. 3 Loading protocol. Phase 1: Baseline tensioning at a rate of 2 mm/s. Phase 2: The force of 10N was maintained for 15 s. Phase 3: The tension was increased by driving the machine at a constant rate of 0.2 mm/s until a force of 100 N was achieved. Phase 4: Loading to failure was finally achieved by driving the machine at a rate of 2 mm/s

Statistical analysis

The necessary number of samples needed for testing was determined taking into account previous reports of F_{max}. Assuming a mean F_{max} value of 250 N, and a standard deviation of 15% (37.5 N), the necessary sample size to detect a relevant difference of 50 N per group was found to be 16, given a power (α) of 0.8 and $p < 0.05$. Normality of distribution was assessed using the Shapiro–Wilk test. Normally distributed data were presented as mean ± standard deviation (SD). Analysis of variance (ANOVA) was performed to determine differences between means, with corresponding post hoc analysis. Linear regression was performed to determine factors influencing dehiscence. Analysis was performed using SPSS (Version 24, IBM Inc., Armonk, NY).

Results

All evaluated outcome measures for each of the three repair groups illustrating the means, standard deviations (SD) per group are shown in Table 2.

Differences between the three groups based on ANOVA and corresponding post hoc analysis were noted for elastic capacity and elastic modulus. Anchor fixation demonstrated a significantly lower mean elastic capacity than both transosseous fixation and Krackow fixation (20.0 ± 8.88 vs 30.14 ± 9.65 and 43.35 ± 4.10%, $p = 0.006$ and 0.012, respectively) (Fig. 4a). Furthermore, krackow fixation demonstrated a significantly higher elastic modulus than both transosseous and anchor fixation (53.38 ± 12.86 versus 35.66 ± 10.24 and 33.98 ± 10.79, $p < 0.001$, respectively) (Fig. 4b). There were no significant differences between the three repair groups regarding F_{max}, F_{3mm}, settling behaviour or stiffness (p = n.s) (Fig. 5).

Based on the linear regression model, the elastic capacity of the tendon-repair construct was the only factor to show a direct influence on F_{3mm}, with a β of 0.7, confidence interval (CI) 0.4; 1.0, $p < 0.001$ (Fig. 4).

None of the parameters: stiffness, elasticity, elastic modulus, tendon diameter, settling behaviour, or fixation technique showed an influence on F_{max} (n.s) as demonstrated by the linear regression model.

Table 2 The mean and standard deviation of all evaluated outcome measures per group of repair

	Krackow	Transosseous	Anchor	*p* value
Settling behaviour (%)	32.73 ± 8.13	32.18 ± 2.97	30.39 ± 3.17	n.s
F_{max} (N)	629.81 ± 49.84	599.31 ± 65.73	617.56 ± 60.25	n.s
F_{3mm} (N)	41.20 ± 9.74	40.42 ± 13.95	33.81 ± 7.85	n.s
Stiffness (N/mm)	18.64 ± 2.71	18.71 ± 2.57	19.64 ± 4.53	n.s
Elastic capacity (%)	49.96 ± 4.1	50.69 ± 9.65	41.48 ± 8.88*	0.003
Elastic modulus (N/mm^2)	53.38 ± 12.86*	35.66 ± 10.24	33.98 ± 10.79	< 0.001

*Value differs significantly from each of the other two groups

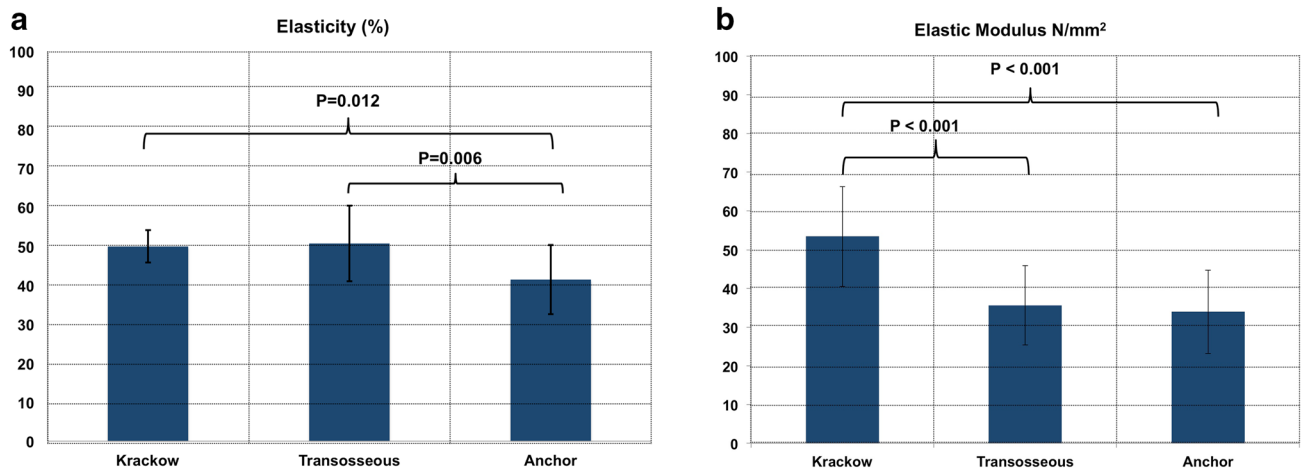

Fig. 4 **a** Bar graph illustrating the elasticity per repair group with corresponding *p* values. **b** Bar graph illustrating the elastic modulus per repair group with corresponding *p* values

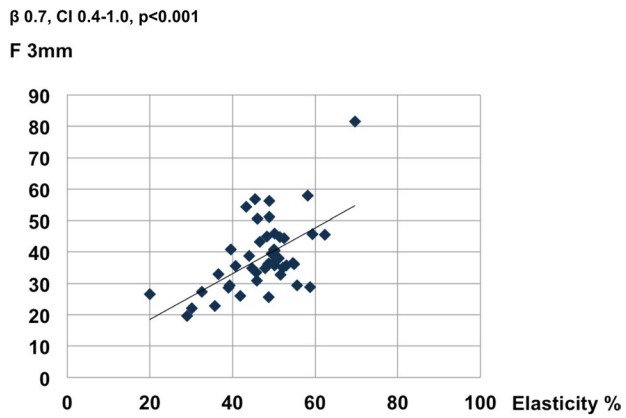

Fig. 5 Scatter blot illustrating the relationship of elasticity of the construct and the force needed to induce a gap of 3 mm based on the linear regression model

Discussion

The most important finding of this study showed that the elastic capacity of a tendon-repair construct impacts the force necessary to induce gapping in the repair zone.

The results also showed that the three methods of repair (Krackow, transosseous and anchor fixation) differed slightly in elastic properties, though the differences were too small to pose an effect on the capacity of withstanding forces. Therefore, this study could not demonstrate superiority of any of the three fixation techniques to one another.

The novelty aspect of the current study is highlighted in the fact that the primary measure was the force necessary to induce true gapping between the ruptured ends of the repaired tendon. Common previous investigative practice was to utilize experimental output measures provided by the MTS, which account for displacement between the loading arms, though not capturing actual gapping between the tendon ends [18]. A modification of the experimental design with the application of an external optic device was necessary to capture dehiscence in the current study allowing for evaluation of further outcome parameters. This method has fortunately also been adapted by a minority of recent studies [15, 21]. Some were based on manual gap measurement using calipers [1, 12].

It can be assumed that gapping as an outcome parameter is possibly of greater clinical relevance than failure thresholds. In this study, it was also possible to delineate that only one-tenth of the force that would cause failure of a tendon-repair construct was sufficient to produce a clinically relevant gap between the tendon ends. It was previously demonstrated by Gelberman that a gap of 3 mm is the maximum to be accepted for assurance of adequate tendon healing, underlining that larger gaps are associated with increased rupture rates and insufficient range of motion [6]. The value has been accepted by several authors [17]. This allows the relevance of the findings of this study to be highlighted, since the likely exposure to small forces may lead to gap formation that may ultimately render the repair insufficient. This would emphasize the significance of strict rehabilitation protocols, especially for tendons around weight-bearing joints. Elongation resultant to gapping is not only likely to increase the risk of re-rupture, but also the altered build-up of force within the lengthened tendon would lead to further deterioration of biomechanics [6, 17].

This study underlines two main aspects that might deserve consideration in future work in the field. The first highlights implications on the planning of future biomechanical studies, which should consider gapping and elasticity of the

repair constructs, being of clinical relevance, which can only be accounted for with the use of an external device enabling capture of motion. The second aspect represents a postulation of an ideal tendon-repair construct as one having a high capacity to elongate before gapping would take place, as this would ultimately lead to the ability to withstand larger forces. Any material or device designed for repair purposes should pose properties with consideration of these aspects.

Furthermore, the model itself as a porcine tendon-repair model for energy large energy transferring tendons proved to be feasible and efficient for standardized biomechanical examination of tendon-repair units.

The primary limitation of this study was that the testing did not involve a cyclic loading protocol simulating the rehabilitation period. However, the primary question was to evaluate the novel study design and identify factors influencing gapping, which would not mandate the application of a cyclic protocol. The second limitation would be associated with the porcine model which, as with any other animal model, is associated with a residual risk of conclusions not being fully translatable.

Conclusion

The results of the study reveal that the higher the elastic capacity of a tendon-repair construct, the higher the force necessary to induce a clinically relevant gap in the zone of repair. Furthermore, it was also shown that forces likely to produce a clinically relevant gap lie within one-tenth of the maximum threshold of failure, emphasizing clinical relevance during the rehabilitation phase.

Funding The study was financed by institutional research funds.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The controlled biomechanical study did not require an ethical approval.

Informed consent For this type of study formal consent is not required.

References

1. Boin MA, Dorweiler MA, McMellen CJ, Gould GC, Laughlin RT (2017) Suture-only repair versus suture anchor-augmented repair for achilles tendon ruptures with a short distal stump: a biomechanical comparison. Orthop J Sports Med 5:2325967116678722
2. Ciriello V, Gudipati S, Tosounidis T, Soucacos PN, Giannoudis PV (2012) Clinical outcomes after repair of quadriceps tendon rupture: a systematic review. Injury 43:1931–1938
3. Clanton TO, Haytmanek CT, Williams BT, Civitarese DM, Turnbull TL, Massey MB et al (2015) A biomechanical comparison of an open repair and 3 minimally invasive percutaneous achilles tendon repair techniques during a simulated, progressive rehabilitation protocol. Am J Sports Med 43:1957–1964
4. Cox JT, Shorten PL, Gould GC, Markert RJ, Barnett MD Jr, Laughlin RT (2014) Knotted versus knotless suture bridge repair of the achilles tendon insertion: a biomechanical study. Am J Sports Med 42:2727–2733
5. Dwyer CL, Dominy DD, Cooney TE, Englund R, Gordon L, Lubahn JD (2015) Biomechanical comparison of double grasping repair versus cross-locked cruciate flexor tendon repair. Hand (N Y) 10:16–22
6. Gelberman RH, Boyer MI, Brodt MD, Winters SC, Silva MJ (1999) The effect of gap formation at the repair site on the strength and excursion of intrasynovial flexor tendons. An experimental study on the early stages of tendon-healing in dogs. J Bone Jt Surg Am 81:975–982
7. Gilmore JH, Clayton-Smith ZJ, Aguilar M, Pneumaticos SG, Giannoudis PV (2015) Reconstruction techniques and clinical results of patellar tendon ruptures: evidence today. Knee 22:148–155
8. Grieco PW, Frumberg DB, Weinberg M, Pivec R, Naziri Q, Uribe JA (2015) Biomechanical evaluation of varying the number of loops in a repair of a physiological model of Achilles tendon rupture. Foot Ankle Int 36:444–449
9. Hart ND, Wallace MK, Scovell JF, Krupp RJ, Cook C, Wyland DJ (2012) Quadriceps tendon rupture: a biomechanical comparison of transosseous equivalent double-row suture anchor versus transosseous tunnel repair. J Knee Surg 25:335–339
10. Havulinna J, Leppanen OV, Jarvinen TL, Goransson H (2011) Comparison of modified Kessler tendon suture at different levels in the human flexor digitorum profundus tendon and porcine flexors and porcine extensors: an experimental biomechanical study. J Hand Surg Eur Vol 36:670–676
11. Huri G, Bicer OS, Ozgozen L, Ucar Y, Garbis NG, Hyun YS (2013) A novel repair method for the treatment of acute Achilles tendon rupture with minimally invasive approach using button implant: a biomechanical study. Foot Ankle Surg 19:261–266
12. Jordan MC, Boelch S, Jansen H, Meffert RH, Hoelscher-Doht S (2016) Does plastic suture deformation induce gapping after tendon repair? A biomechanical comparison of different suture materials. J Biomech 49:2607–2612
13. Jordan MC, Hoelscher-Doht S, Fehske K, Gilbert F, Jansen H, Meffert RH (2015) Bunnell or cross-lock Bunnell suture for tendon repair? Defining the biomechanical role of suture pretension. J Orthop Surg Res 10:192
14. Kanz BN, Morris RP, Lewis T, Panchbhavi VK (2014) Biomechanical evaluation of a knotless barbed suture repair in a human Achilles tendon rupture model. Foot Ankle Spec 7:176–181
15. la Fuente C, Cruz-Montecinos C, Schimidt HL, Henriquez H, Ruidiaz S, Carpes FP (2017) Biomechanical properties of different techniques used in vitro for suturing mid-substance Achilles tendon ruptures. Clin Biomech (Bristol Avon) 50:78–83
16. Lantto I, Heikkinen J, Flinkkila T, Ohtonen P, Leppilahti J (2015) Epidemiology of Achilles tendon ruptures: increasing incidence over a 33-year period. Scand J Med Sci Sports 25:e133–e138
17. Rawson S, Cartmell S, Wong J (2013) Suture techniques for tendon repair; a comparative review. Muscles Ligaments Tendons J 3:220–228
18. Sadoghi P, Rosso C, Valderrabano V, Leithner A, Vavken P (2012) Initial Achilles tendon repair strength—synthesized biomechanical data from 196 cadaver repairs. Int Orthop 36:1947–1951
19. Saragaglia D, Pison A, Rubens-Duval B (2013) Acute and old ruptures of the extensor apparatus of the knee in adults (excluding knee replacement). Orthop Traumatol Surg Res 99:S67–S76

20. Smith AM, Forder JA, Annapureddy SR, Reddy KS, Amis AA (2005) The porcine forelimb as a model for human flexor tendon surgery. J Hand Surg Br 30:307–309
21. Van Dyke RO, Chaudhary SA, Gould G, Trimba R, Laughlin RT (2017) Biomechanical head-to-head comparison of 2 sutures and the giftbox versus Bunnell techniques for midsubstance Achilles tendon ruptures. Orthop J Sports Med 5:2325967117707477
22. Yammine K, Assi C (2017) Efficacy of repair techniques of the Achilles tendon: a meta-analysis of human cadaveric biomechanical studies. Foot (Edinb) 30:13–20