■ FOOT & ANKLE

Biomechanical evaluation of two methods of fixation of a flexor hallucis longus tendon graft

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Aims

The traditional transosseus flexor hallucis longus (FHL) tendon transfer for patients with Achilles tendinopathy requires two incisions to harvest a long tendon graft. The use of a biotenodesis screw enables a short graft to be used and is less invasive, but lacks supporting evidence about its biomechanical behaviour. We aimed, in this study, to compare the strength of the traditional transosseus tendon-to-tendon fixation with tendon-to-bone fixation using a tenodesis screw, in cyclical loading and ultimate load testing.

Materials and Methods

Tendon grafts were undertaken in 24 paired lower-leg specimens and randomly assigned in two groups using fixation with a transosseus suture (suture group) or a tenodesis screw (screw group). The biomechanical behaviour was evaluated using cyclical and ultimate loading tests. The Student's *t*-test was performed to assess statistically significant differences in bone mineral density (BMD), displacement, the slope of the load-displacement curves, and load to failure.

Results

The screw group showed less displacement (loosening) during cyclical loading, which was significant during 300, 500, 600, 700, 800, 900, and 1000 cycles ($p < 0.05$: other cycles: $0.079 < p < 0.402$). Compared with the suture group, the screw group had higher mean ultimate load values (133.6 N, SD 73.5 *vs* 110.1 N, SD 46.2; p = 0.416).

Conclusion

Fixation of the FHL tendon with a tenodesis screw enables a less invasive procedure to be undertaken and shows similar biomechanical behaviour and primary strength compared with fixation using a transosseus suture.

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Flexor hallucis longus (FHL) tendon transfer is an established form of treatment for severe Achilles tendinopathy,[1-5] Achilles tendon rupture,[3,6-8] and revision surgery.[9,10] The traditional technique described by Wapner et al[11] involves transosseus tendon-to-tendon fixation and is carried out through a medial midfoot incision in order to harvest a long FHL tendon graft with a second posterior approach to the Achilles tendon. The FHL tendon is looped through a transverse calcaneal bone tunnel and sutured back onto its proximal stump. This technique restores the strength of plantarflexion of the ankle, alleviates pain, and has high patient satisfaction.[2,12,13] Nevertheless, the so called 'long harvest' technique has complications such as intraoperative damage to the medial and lateral plantar nerve,[14,15] excessive soft-tissue scarring,[2,16] and problems of wound healing.[2,13,16,17]

A shorter tendon graft may be used and fixed directly to the calcaneum using a screw, enabling surgery through a single posterior incision, diminishing donor site morbidity. This technique, despite its lower invasiveness, may be biomechanically inferior to tendon-to-tendon fixation, which would contraindicate its clinical application. There is little information about the biomechanical behaviour of these two techniques for FHL tendon transfer. Our aim, in this study, was to compare the strength of the traditional transosseus tendon-to-tendon fixation with the newer tendon-to-bone fixation using a tenodesis screw, in cyclical loading and ultimate load testing.

Materials and Methods

A total of 24 paired specimens of human lower legs, which were obtained from donors to the

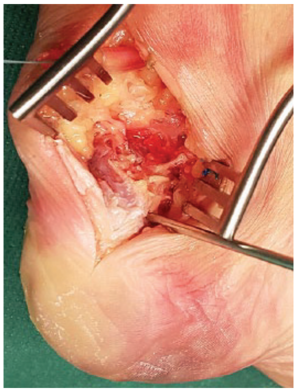

Fig. 1a

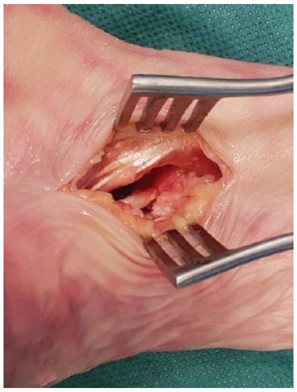

Fig. 1b

Fig. 1c

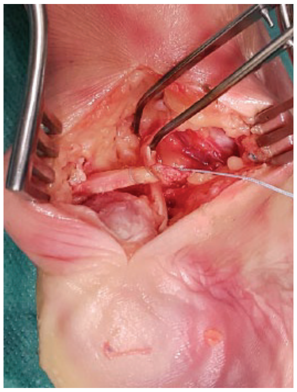

Fig. 1d

Photographs showing the 'long harvest' method. a) The first incision was proximal to the calcaneum. b) The flexor hallucis longus tendon is identified and transected through a second incision in the medial aspect of the foot. c) The tendon was prepared with a 2-0 FiberLoop and d) passed through a transverse tunnel in the calcaneum from dorsal to plantar, looped to itself, and sutured.

Centre for Anatomy and Cell Biology, Medical University of Vienna were used. The donors had given written consent for their bodies to be used for research and education. The study was approved by the Ethics Committee of the Medical University of Vienna (1892/2014). The mean age of the seven female and five male donors was 77.2 years (SD 8.5; 64 to 92). In order to prevent any change in the mechanical properties of the soft tissues, the specimens were fresh frozen at -80°C and exposed to room temperature 48 hours prior to preparation. They were also kept moist with 0.9% NaCl saline solution during the preparation and tested at room temperature.

The FHL tendon was harvested through a medial incision above the Achilles tendon extending to the medial side of the foot. It was exposed from the musculotendinous junction, carefully separated from surrounding structures and mobilized to its insertion into the great toe. The calcaneum was prepared by mobilizing the peroneal tendons, the tibialis posterior, and the flexor digitorum longus tendon. The subtalar, calcaneocuboid and calcaneonavicular ligaments were then dissected. Finally, the calcaneum was exarticulated (i.e. removed without cutting the bone).

Any specimen with evidence of an injury or of surgery to the foot or ankle, or degenerative changes of tendon or bone was excluded. Thus, two specimens with evidence of osteoporosis and one with degenerative changes in the FHL tendon were excluded. A total of 21 specimens proved eligible for inclusion.

Prior to preparation and biomechanical testing, the bone mineral density (BMD) was measured with dual-energy X-ray absorptiometry (DXA) scans of the calcaneum, using a Lunar Prodigy series densitometer (GE Lunar Prodigy; GE Healthcare, Chicago, Illinois). Excellent repeatability of DXA measurements has been reported using this technique.[18]

Specimens were randomly divided into two groups: the tendon-to-tendon (suture) and tenodesis fixation (screw) groups. A single senior foot and ankle surgeon (RS) performed both reconstructions in all specimens in order to achieve optimal and consistent fixation. Tenodesis of the FHL tendon to itself was performed as the worst case clinical scenario in order to evaluate the isolated stability of both fixations of the tendon and mimic irreparable Achilles tendinopaphy.[8]

Each FHL tendon was prepared with a 2-0 FiberLoop (Arthrex Inc., Naples, Florida) with a straight needle and using the SpeedWhip technique (Arthrex Inc.). In suture group specimens (Fig. 1), a transverse bone tunnel was placed in a mediolateral direction on the posterosuperior aspect of the tuber calcanei and the tendon was passed from medial to lateral. It was then looped to itself and sutured with the 2-0 FiberWire (Arthrex Inc.). Three stitches were applied in a simple eight suture technique according to Wagner et al.[19]

For the screw group (Fig. 2), a tunnel was placed in a dorsoplantar direction in the posterior aspect of the tuber calcanei. The distance between the most posterior portion of the insertion of the Achilles tendon and the tunnel was 1 cm. A guide wire was introduced and a cannulated 5 mm drill was used to create the tunnel. The sutured FHL tendon was then passed from dorsal to plantar. After tensioning the graft, it was fixed using a biodegradable poly-L-lactide acid (PLLA) interference screw: 6.25 mm × 15 mm Bio-Tenodesis Screw (Arthrex Inc.).

All experiments were carried out at the Adolf Lorenz Lab for Biomechanics at the Medical University of Vienna. The setup was designed to mimic *in vivo* loading of the FHL tendon transfer (Fig. 3). The anterior calcaneum of all specimens was potted in Wood's metal in 40 mm diameter, custom-built steel cups, allowing them to be mounted in a servohydraulic load frame, 858 Mini Bionix (MTS Systems Corporation, Eden Prairie, Minnesota). The sustentaculaum tali of each specimen was osteotomized in larger specimens in order to fit the cups. The specimens were rigidly fixed in an industrial vice with the hindfoot dorsiflexed by 30° in relation to the tibia in order to simulate early heel rise.[20,21] The proximal end of the FHL tendon was clamped 7 cm proximal to the insertion. Approximately 5 cm of the tendon and muscle belly were held with a custom-designed cryo-fixation clamp with sawtooth grips to prevent slippage of the tendon in tension.[22] Slippage

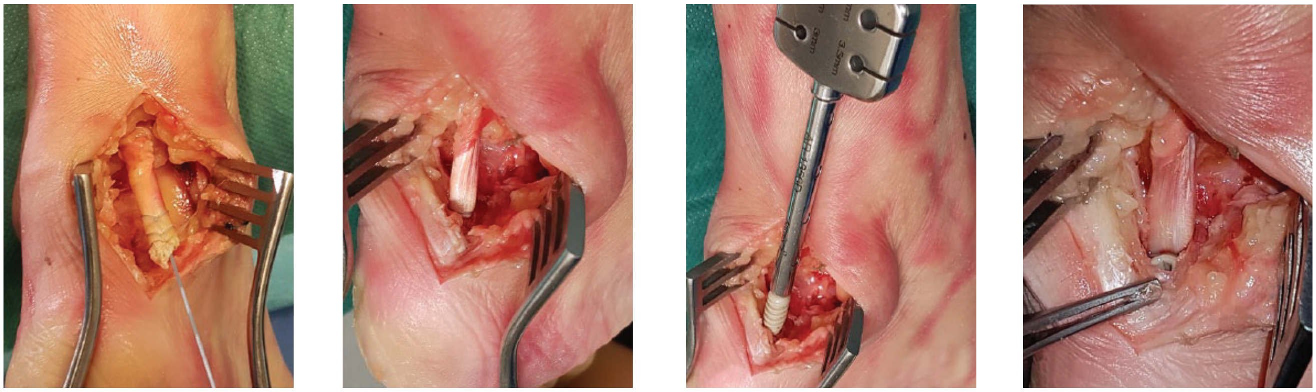

Fig. 2a

Fig. 2b

Fig. 2c

Fig. 2d

Photographs showing the ‘short harvest’ method. a) The FHL tendon was identified using an incision proximal to the calcaneum, prepared with a 2-0 FiberLoop, and b) passed through a tunnel in the tuber calcanei in a dorsoplantar direction. c) A 6.25 mm × 15 mm screw is used d) to fix the prepared FHL tendon.

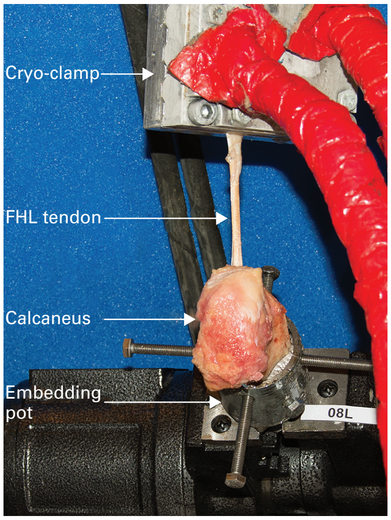

Fig. 3

A photograph of the setup. The calcanei were fixed with Wood’s metal in the embedding pots mimicking conditions of an early heel rise. The proximal part of the FHL tendon was fixed in a cryo-fixation clamp. The tendon was loaded axially with 1000 cycles, followed by a quasi-static ultimate load test.

was monitored by a marking at the most distal aspect of the tendon. A maximum temperature of -15°C of the cryo-fixation clamp was monitored at the site of insertion using a conventional laser thermometer.

Prior to each test, all specimens were preloaded to eliminate play between them and the test setup, followed by a relaxation to 0 N. After that, a cyclical tensile force with an amplitude of 60 N at 1 Hz was applied in line with the tendon for 1000 cycles under load control. Finni et al[23] reported peak *in vivo* Achilles tendon loads of 1430 N ± 500 N during walking. Giddings et al[24] calculated, in a numerical model, peak loads for the Achilles tendon of 3.9 times bodyweight during walking. In both cases, loads were significantly greater than the strength of the constructs tested in pilot experiments. The load amplitude of 60 N conformed with 50% of the maximum strength in pretests, ensuring that the first test cycles would not initiate deformation and irreversible damage to the specimen or the reconstruction. A similar approach was used by Beitzel et al[21] and Herbort et al,[25] who compared two techniques of repair of the Achilles tendon using suture anchors. This step was followed by a second tensile cycle until failure at a quasi-static rate of 0.1 mm/s to determine the ultimate load. The measurement transducer for the axial displacement and force were integrated into the 858 Mini Bionix testing system. Force and displacement were digitalized with the sample rate of 100 Hz.

Statistical analysis. The Student’s *t*-test was performed to analyze statistically significant differences in BMD, displacement, the slope of the load-displacement curves, and ultimate load in each repair model. Pearson’s product-moment correlation coefficient (R) was computed to investigate linear correlations between: 1) age and ultimate loads and 2) BMD and ultimate loads. Statistical significance was set at the 95% confidence level (CI), with p-values of < 0.05. Each group was tested for normal distribution using Shapiro–Wilk test. The analysis was performed using IBM SPSS Statistics 24 (IBM Corp., Armonk, New York).

Results

The mean BMD of the specimens was 0.555 g/cm² (SD 0.172; 0.380 to 0.825) for the suture group and 0.545 g/cm² (SD 0.237; 0.203 to 0.928) for the screw group. There was no statistically significant difference between the groups ($p = 0.907$).

Figure 4 illustrates the displacement of both groups measured at 10, 100, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 cycles. The displacement describes the visco-elastic and the plastic deformation (loosening) of the construct. There was a statistically significant difference in displacement at 300, 500, 600, 700, 800, 900, and 1000 cycles (all $p < 0.05$) but no statistically significant differences at any other cycle: 10, 100, 200,

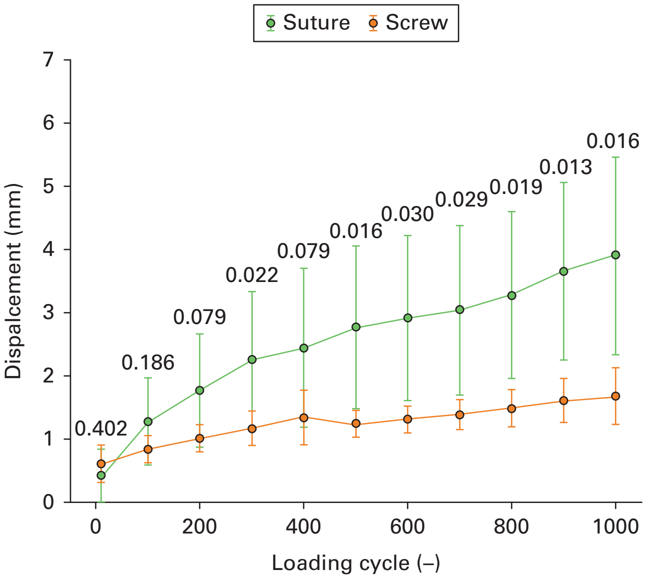

Fig. 4

Dot-and-whisker plot showing the displacement of the suture and screw group for each cycle and p-value for comparisons. Dots represent the means; whiskers represent the standard deviation. The number given above the top of each pair of whiskers is the p-value.

Fig. 5

Graph showing the typical load-displacement curves for the ultimate load tests.

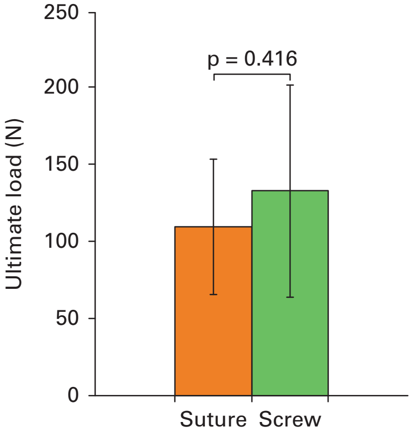

Fig. 6

Graph showing a summary of the results for ultimate load (mean and SD). A statistically significant difference between the means of the two groups was not observed (p = 0.416).

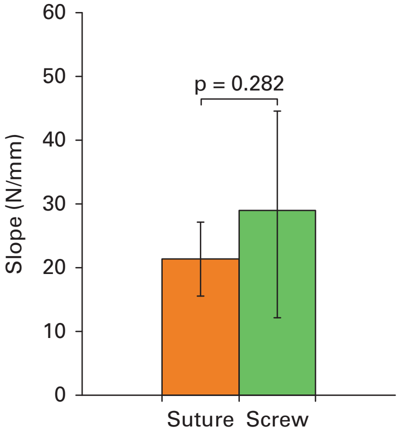

Fig. 7

Graph showing the summary for the slope (mean and SD). The difference between the means of the two groups was not statistically significant (p = 0.0282).

400 ($0.05 < p < 0.402$). The variations of the displacements were statistically significantly different for 300 and 500 cycles ($p = 0.036$ and $p = 0.045$, respectively) and were not significantly different for any other cycle ($0.056 < p < 0.471$).

Examples of typical load-displacement curves from the ultimate load test for the two groups can be seen in Figure 5.

The ultimate load was calculated as the maximum load achieved in the ultimate load test or the maximum load withstood by the construct during cyclic loading. It was 110.1 N (SD 46.2; 20.8 to 158.1) in the suture group and 133.6 N (SD 73.5; 29.2 to 243.8) in the screw group (Fig. 6).

The mean ultimate load in the two groups was not statistically significantly different ($p = 0.416$, 95% CI -83.89 to 36.99). The mean slope of the load-displacement curves in the load to failure tests for the suture group (21.44 N/mm (SD 5.79; 15.53 to 31.30) was not statistically significantly different from that in the screw group (28.35 N/mm, SD 16.05; 6.13 to 46.62) ($p = 0.400$, 95% CI -26.53 to 12.70) (Fig. 7). We would like to note that we used the term slope of the load-displacement curve instead of stiffness, as is frequently found in the literature.[26,27] Stiffness measures the resistance offered by an elastic body to deformation. Tendons, but also bone,[28] however, show both viscous and elastic behaviour.

Table I. Survival of the constructs for each cycle

Cycle	0	10	100	200	300	400	500	600	700	800	900	1000
Suture	12	9	9	9	9	8	8	8	8	8	8	8
Screw	9	6	6	6	6	6	5	5	5	5	5	5

BMD was predictive of ultimate load in the screw group, but not in the suture group ($R^2 = 0.71$ and $R^2 = 0.21$, respectively).

Four of 12 (33%) and four of nine (44%) specimens failed during cycling loading in the suture and screw groups, respectively (Table I).

Ten specimens (83%) in the suture group failed by the suture tearing through the tendon (tendon-suture interface failure) and two (17%) by the tendon cutting through the calcaneum (bony tunnel failure). In the screw group, six (67%) failed due to tendon pullout (tendon-screw interface); in two (22%), the screw was pulled out of the bone (screw-bone interface failure) and in one (11%), a rupture of the FHL tendon occurred (tendon failure). The ultimate load in this latter specimen was among the highest at 220 N.

Discussion

These results showed no reduction in stability under cyclical loading when the Bio-Tenodesis Screw System was used in the attachment of the FHL tendon to the calcaneum compared with the conventional suture technique. The screw fixation achieved a slightly higher slope in the load-displacement curves and ultimate load; however, these results were not statistically significant. The two methods of fixation showed similar resistance to deformation as shown by the slope of the load-displacement curves. Cyclical loading more closely mimics physiological loading conditions during exercise and activities of daily living, whereas single ultimate load tests simulate the maximum tolerated load until failure of the construct. There was a statistically significant difference in displacement in seven of 11 loading cycles, showing a tendency towards less loosening of the screw construct. The standard deviation of the screw construct was generally lower (< 0.5 mm) compared with the suture group (Fig. 5); however, the variations were significantly lower in the screw group only in two loading cycles. While these differences are not clinically relevant, the less invasive short harvest method was not biomechanically inferior when compared with the sutured ‘long harvest’ method. There was a positive correlation between BMD and the ultimate load in the screw group, but not with the suture group. This seems plausible, as a screw will have a better hold in denser material and the load has to be increased in order to pull out the tendon or the tendon with the screw. Hence the specimens from the screw group, which failed during cyclical loading, had the lowest BMDs. Further research could clarify this issue.

The use of a bio-tenodesis screw for fixation of the FHL tendon graft eliminates extensive surgical exposure for a long tendon harvest and transosseus looping of the tendon through the calcaneum. Besides the apparent surgical and clinical advantages of the use of a screw, the stability of the initial construct has not been fully investigated. Finni et al[23] reported a mean load of 1430 N (750 to 2360) in the Achilles tendon. The technique which is presented here, and the subsequent treatment, aim to restore the biomechanical behaviour of the native Achilles tendon completely. Treatment after repair of the Achilles tendon includes immobilization for six to eight weeks.[17] The FHL tendon transfer described here for Achilles tendinopathy and the experimental setup clearly do not replicate clinical reality, but compare the biomechanical behaviour of two techniques. Fixation of the FHL tendon should be stable enough to allow weight-bearing during rehabilitation. The safe use of early mobilization requires a strong primary repair.[29] Cyclical loading replicates the physiological loading of initial mobilization and weight-bearing.

Some biomechanical studies have already addressed FHL tendon transfer. Recently, Drakos et al[26] compared suture anchor fixation with tenodesis and found the mean ultimate load to be 188.8 N (SD 25.8) in the anchor group and 171.6 N (SD 39.6) in the tenodesis group ($p = 0.759$). The mean stiffness of the construct, as indicated by the slope of the load-displacement curve, showed slightly superior results in the screw fixation (49.7 N/mm, SD 9.3) compared with the anchor group (35.5 N/mm, SD 3.9; $p = 0.008$). They concluded that there was no statistically significant difference in the strength of the fixations between the two forms of fixation. The authors also found a negative correlation between age and failure load. Higher mean values for both the strength and slope of the load-displacement curve (stiffness), compared with present findings, might result from lower donor age (67 *vs* 77.2 years) and fewer loading cycles (100 *vs* 1000) preceding the ultimate load test. Lee et al[30] investigated two modifications of FHL tenodesis screw fixation, with and without the use of a terminal whipstitch, in fresh frozen human bones and synthetic bone blocks. They also investigated the difference in the strength of the construct between fixation with unicortical (blind) and bicortical (complete) drilling of the calcaneal tunnel. Whipstitched tendons showed a significantly higher mean ultimate load (294.3 N *vs* 194.5 N, $p = 0.001$) compared with the non-whipstitched tendons in synthetic bone. There was no difference in the strength of fixation between those in whom the calcaneal tunnel was drilled blind and those in whom it was complete ($p = 0.07$). The tendon-screw interface was the most common site of failure in the complete tunnel group, which corresponds to our findings. Most failures occurred at the bone-screw interface in the blind tunnel group. A recent study[27] showed similar ultimate load, peak stress, Young’s modulus, failure strain, and strain energy when screw fixation and a bone tunnel were used. Both methods showed mean ultimate load values of about 230 N ($p = 0.83$). This similarity was also found in the current study, while higher ultimate loads probably resulted from the lower mean age (46 years) and higher body mass index (BMI) of the donors. Interestingly, the authors found a significant age-related decrease in the ultimate load and Young's modulus. An analysis of the BMD was not reported. Similarly, Sullivan et al[31] recorded a mean ultimate load of 142 N for both the tendon-to-tendon and tendon-to-bone fixation using suture anchors in the transfer of flexor digitorum longus (FDL) to the navicular, without a statistically significant difference. Also studying the transfer of the FDL tendon to the navicular, Sabonghy et al[32] reported significantly higher mean ultimate loads for tendon-to-tendon compared with tendon-to-bone fixation (279 N and 148 N, respectively). The specimens had a lower mean BMD and the authors used larger interference screws (7 mm × 20 mm to 25 mm) than in our study. The angle at which the force was applied in the bone tunnel was not clearly described. This angle can have a significant influence on the strength of the fixation. However, the tendon was also sutured to the surrounding periosteum in the tendon-to-tendon fixation and this was also done in another study on FDL tendon transfer to the navicular, with similar results.[33] The tendon-to-tendon transfer also showed higher ultimate loads compared with tendon-to-bone fixation (459 N *vs* 327 N, respectively) in 24 specimens with a mean age of 38 years. Loading of > 1000 cycles revealed no significant differences in displacement in the same study.[33]

To the best of our knowledge, the present study evaluates, for the first time, the biomechanical stability in cyclical loading and ultimate load tests related to the BMD for the traditional transosseus and tenodesis screw fixation. Analysis of the modes of failure revealed two failures of the bony tunnel (17%) in the suture group by cut-out, and two screw pull-outs (22%) in the screw group. The most common mode of failure in the suture group was suture pull-out through the substance of the tendon, which corresponds to previous findings.[21,25,27,31,34] The most common mode of failure in the screw group was a tendon pull-out at the tendon-screw interface, which also corresponds to the findings of Lee et al[30] using the same technique.

The study has limitations. First, the biomechanical setup limits the application of the findings in routine clinical practice. Simulation of accurate *in vivo* conditions in biomechanical studies is difficult and deviates from simplified models with simulated pathologies. In order to evaluate the isolated stability of the forms of fixation, a tenodesis of the FHL tendon to itself was performed, while suture to the Achilles tendon is undertaken, whenever possible, in clinical practice. Also, only a single strand of the FHL tendon was used in the tendon-to-tendon fixation, as commonly performed in similar studies.[27,32,33] Clearly this resulted in lower load values and would represent the clinical worst-case scenario.

The angle of pull on the FHL tendon by the load cell may also not be similar to physiological forces during walking. Early heel rise was simulated in the test setup with an angle of 30° dorsiflexion of the calcaneum. However, this variable remained constant throughout testing allowing easier reproduction of the data. Second, due to the exclusion of three specimens in the screw group prior to biomechanical testing, a paired statistical analysis could not be undertaken. Nevertheless, analysis of the BMD revealed similar results in both groups, suggesting minimal intergroup variations. In addition, the power of the study was limited due to the small size of the groups and high age of the donors.

However, in conclusion, beside its advantage as being less invasive, the 'short harvest' method for FHL tendon transfer using tenodesis screw showed similar biomechanical behaviour compared with a classical transosseus fixation method.

Take home message:

- The use of a bio-tenodesis screw enables a short flexor hallucis longus (FHL) tendon harvest and is less invasive compared with the traditional transosseus suture fixation in FHL tendon transfer in Achilles tendinopathy.
- Bio-tenodesis screw fixation of the FHL tendon shows similar biomechanical behaviour and primary stability compared with transosseus suture fixation.
- Biomechanical data justifies the use of the less invasive method.

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Author contributions:

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F. Wenzel: Preparing the specimens, Drafting and approving the manuscript.

L. Hirtler: Preparing the specimens, Revising and approving the manuscript.

S. Zandieh: Radiological investigations, Approving the manuscript.

R. Windhager: Designing the study, Revising and approving the manuscript.

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