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Mechanical Properties of Reconstructed Achilles' Tendon with Transfer of Peroneus Brevis or Flexor Hallucis Longus Tendon

AQ: 1 **S. Hermann,[1] B. Datta, N. Maffulli,[2] M. Neil,[3] and W. R. Walsh[4]**

Treatment of chronic Achilles' tendon ruptures can be technically difficult because of tendon retraction, atrophy, and short distal stumps. Surgical repair of chronic Achilles' tendon ruptures focuses on local and free tendon transfers, as well as reconstruction with allografts or synthetic materials. This study examined the in vitro mechanical properties of a reconstructed Achilles' tendon with the peroneus brevis or the flexor hallucis longus tendons in a human cadaver model. The tendons were harvested from 17 fresh-frozen human cadavers, and the same techniques were used for all of the model reconstructions. Biomechanical measurements included the failure load, stiffness, energy-to-peak load, and mode of failure. The mean failure load was significantly higher in the peroneus brevis group ($P = .036$*), and there was no significant difference in stiffness and energy-to-peak load between the peroneus brevis and flexor hallucis longus groups. In every case, the mode of failure involved the tendon graft pulling through either the distal or proximal stump of the Achilles' tendon. The greater failure loads observed with the use of peroneus brevis may not be clinically relevant, however, because of the magnitude of the peak loads observed in the cadaveric model. The present study supports the use of either peroneus brevis or flexor hallucis longus for reconstruction of chronic Achilles' tendon ruptures and indicates the need for surgeons to carefully reinforce the attachment of the transferred tendon grafts to the stumps of the Achilles' tendon to prevent pullout.* (The Journal of Foot & Ankle Surgery xx(x):xxx, 2007)

Key Words: Achilles' tendon, materials testing, tendon rupture, tendon transfer

During the last few decades, the incidence of Achilles' tendon (AT) ruptures has been observed to increase, with men in middle age forming the majority of patients diagnosed with the condition (1–3). Although clinical examination can be used to identify rupture of the AT (4), and real-time high-resolution ultrasonography and magnetic resonance imaging (MRI) enable accurate diagnosis in clinically doubtful cases, about 10% to 20% of acute ruptures remain undiagnosed initially (5). In such cases, delayed diagnosis leads to neglect of the AT rupture, and a state of chronic rupture ensues without union of the proximal and distal stumps of the tendon. Treatment of chronic AT ruptures can be technically demanding because of retraction and atrophy of the tendon stumps and, in some cases, the presence of a small (short) distal stump. In acute ruptures, conservative management in selected patients may lead to satisfactory results, although the incidence of rerupture is known to be considerably higher in cases that are treated without surgical intervention (6). For chronic ruptures of the AT, surgery is regarded as the management of choice (5, 7–16).

Surgical management for chronic ruptures of the AT may include local transfer of either the flexor hallucis longus (FHL) or peroneus brevis (PB) tendon (13, 16–18), free tendon transfer from a distant anatomical site (12), or the use of allograft (14) or synthetic materials (15) to reconstruct the tendon defect. Reconstruction of AT defects with autologous tendon grafts, such as FHL or PB, or the use of distant grafts such as gracilis, have been shown to yield satisfactory clinical results (12, 13, 16, 18). Although rare, rerupture after such procedures is a major late complication (19). Factors contributing to failure of AT reconstructions may include inadequate postoperative management or lower mechanical strength of the repair. In an effort to better

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understand the biomechanical properties of autologous local tendon grafts for the repair of the ruptured AT, we undertook an investigation to examine the time 0 in vitro mechanical properties of a reconstructed AT with PB or FHL tendon in a human cadaver model.

Materials and Methods

ATs, inclusive of the calcaneal insertion and the distal portions of the triceps surae, as well as the tendons of FHL and PB were harvested from 17 fresh-frozen human cadaver specimens. The FHL tendon was detached just proximal to the knot of Henry and the PB tendon close to its insertion into the fifth metatarsal base. Specimens were excluded if there was any evidence of grossly visible or palpable pathology such as nodularity or atrophy or indications of previous rupture or surgery. After being harvested, the tendons were stored in phosphate-buffered saline solution at −20°C until approximately 4 hours before testing, when the specimens were thawed to room temperature. Specimens were thawed to room temperature for 4 hours before reconstruction on the day of testing. The AT reconstructions were always performed with grafts from the same cadaver specimen, and the same surgical techniques, described below, were used for all of the AT reconstructions.

The cadaveric AT rupture model consisted of making a 4-cm transverse incision through the full thickness of the tendon at a level 2.5 cm proximal to its insertion into the calcaneus. The FHL or PB tendon grafts were passed transversely in either a medial-to-lateral direction, for FHL, or lateral-to-medial, for PB, through a small incision located 1 cm distal to the proximal margin of the distal stump (Fig 1). The transferred tendon was then pulled proximally and passed through a small incision located 1 cm proximal to the distal margin of the proximal stump. A #11 scalpel blade was used to create both the distal and proximal AT stump incisions through which either the FHL or PB tendon was transferred, and care was taken to keep the fit very snug as the transferred tendon was passed through the distal and proximal portions of the simulated rupture of the AT. Furthermore, the transferred tendon was stitched to the adjacent portion of the AT with interrupted and circumferential sutures of 3-0 Vicryl (polyglactin 910; Ethicon, Inc., North Ryde, Australia) at each entry and exit point to minimize the risk of the transferred tendon pulling out of the AT.

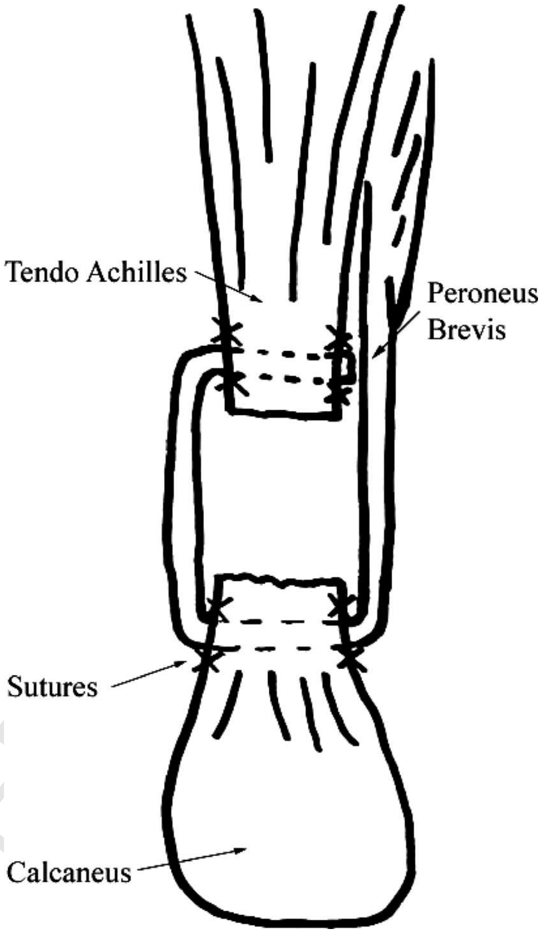

FIGURE 1 Repair technique with peroneus brevis tendon (posterior view). A circumferential 3-0 multifilament absorbable suture was used to augment the repair, which was passed through the Achilles' tendon.

Biomechanical testing was performed with an 858 Mini Bionix testing system (MTS Systems Corporation, Eden Prairie, MN). The proximal part of the tendon reconstruction model was secured in a brass clamp (Fig 2). To prevent slippage and to ensure that the soft tissues were securely attached to the testing apparatus, the brass clamp and the tendon gripped within the clamp were frozen with liquid carbon dioxide for 1 minute before loading the tendon to prevent slippage (20). Care was taken to avoid freezing any of the soft tissues outside of the brass clamp by dripping room temperature phosphate-buffered saline solution over those tissues during the freezing phase. Distally, the calcaneus was seated in a U-shaped jig and attached with a metal bolt that was positioned through a transverse drill hole in the body of the calcaneus, thereby rigidly fixing the bone to the testing machine (Fig 2). When necessary, some of the width of the bone was removed with a sagittal saw to assure a snug fit in the U-shaped jig. The reconstructed AT model was then pulled to failure by application of an axial tensile load that was imparted to the construct at a rate of 100% per minute. The load and displacement were measured at 100 Hz with a personal computer and an integrated suite of testing applications (Software TestWorks SX; Software Research, Inc., San Francisco, CA). The failure load (N), stiffness (N/mm), energy to peak load (J), and the mode of failure were recorded for each specimen. The failure load was defined as the maximum amount of tensile force ap-

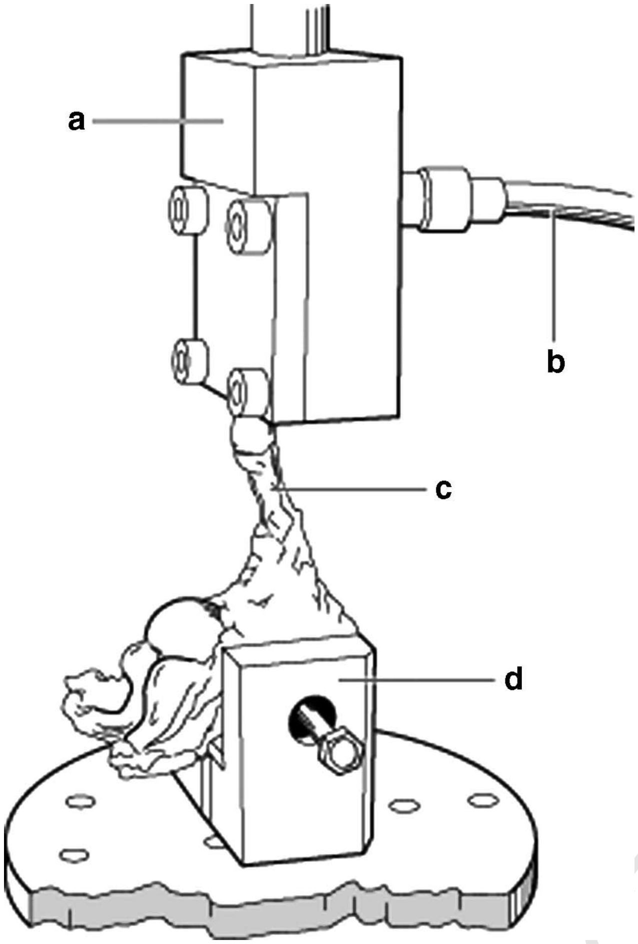

FIGURE 2 Setup for biomechanical testing with calcaneus fixed in U-clamp and proximal Achilles' tendon stump in brass grips that were infiltrated with liquid carbon dioxide.

plied to the construct, and the amount of load per unit of displacement was used to define the stiffness. Energy was defined as the area under the curve to maximum failure load. The mode of failure was described as the observed site and method of tendon separation. The continuous numeric data were analyzed with the Student *t* test, and the categorical data were analyzed with the Fisher exact test to determine whether statistically significant differences were present for failure modes. Statistical significance was defined at the 5% level, and SPSS (SPSS Inc., Chicago, IL) for Windows (Microsoft Corporation, Redmond, WA) was used for the analysis.

Results

A total of 9 PB and 8 FHL reconstructions were prepared for mechanical testing, and the mean age (at the time of death) of the cadaveric specimens was 71.1 ± 4.9 years. All of the AT reconstruction models were successfully tested, except for 1 of the PB transfer specimens that failed to meet the inclusion criteria because the tendon construct slipped from the proximal clamp (at 360.37 N) before disruption of any of the fibers of the transferred tendon or of the AT. Therefore, a total of 16 specimens, 8 PB and 8 FHL, were tested to failure. Initially, deformation of the AT reconstructions demonstrated a nonlinear relationship between load and displacement. This was followed by a period where displacement and load increased in a linear manner until the tendon constructs failed. The mean failure loads, stiffness of the reconstruction, energy to failure, and mode of failure for all of the reconstructions are presented in Table 1. Statistical analysis revealed that the failure load of AT reconstructions with local transfer of PB was significantly higher compared with reconstructions with local transfer of FHL ($P = .036$). There were no statistically significant differences between the PB and FHL groups in regard to construct stiffness ($P = .48$), energy to failure ($P = .12$), and mode of failure ($P = .65$). In all 16 specimens, failure occurred because of pullout of the transferred tendon graft through either the proximal or distal stump of the AT. In regard to transfer of PB (n = 8), 4 (50%) of the specimens failed at the proximal stump and 4 failed at the distal stump. In regard to transfer of FHL (n = 8), 3 (37.5%) of the specimens failed at the proximal stump and 5 (62.5%) failed at the distal stump.

Discussion

AT ruptures that have been neglected, or those that show inadequate union of the tendon stumps, are referred to as chronic ruptures and are amenable to repair by means of a wide range of surgical techniques. Studies that quantify the biomechanical properties of such reconstructions could provide insight into the ability of such repairs to withstand early postoperative loading and different rehabilitation regimens. The local tendon transfer and suture techniques reported in the current study have been reported to be clinically successful (13, 21), and both PB and FHL tendon transfers are routinely used for repair of the chronically ruptured AT (16, 18). Although we were careful to keep the method of tendon transfer and suture constant in all of the specimens that we tested, care must be taken when extrapolating the results of this investigation to other in vitro, and clinical, investigations wherein other tendon transfer and suture techniques are used. In fact, it has been shown that the mechanical properties of tendon repair vary with the size of the suture and pattern of suture application (22, 23).

Data from the current study revealed the ultimate failure load of cadaveric AT reconstructions with PB to be mechanically superior to repairs with FHL. Interestingly, the same general failure mechanism was observed in all of the specimens, wherein the transferred PB or FHL tendon graft pulled through at either the proximal or distal stump of

TABLE 1 Structural properties of cadaveric Achilles' tendon reconstructions (N = 16) with local transfer of peroneus brevis (PB) or flexor hallucis longus (FHL) tendon grafts

Structural property	PB (n = 8)	FHL (n = 8)	*P* value
Failure loads (N)	348.8 ± 124.9	241.5 ± 82.2	.036†
Stiffness (N/mm)	16.5 ± 6.3	14.0 ± 3.8	.48†
Energy to peak load (J)	3656.0 ± 2720.3	2406.7 ± 1621.8	.12†
Failure = distal pullout*	4/8 (50%)	(5/8) 62.5%	.65‡

*Failure = distal pullout: the percentage of specimens that displayed failure by means of pullout of transferred tendon from the attachment to the distal, rather than proximal, stump of the Achilles' tendon.
†Student *t* test.
‡Fisher exact test.

the AT. Because none of the transferred portions of the PB or FHL grafts failed during mechanical testing, it appears that the stumps, either proximal or distal, of the AT may be the weakest structural component of the repair construct. Previous biomechanical tests of tensile strength revealed tendon failure loads of 511.0 ± 164.3 N and 333.1 ± 137.2 N for FHL and PB, respectively (24). In the current investigation, we observed the transferred segments of FHL and PB to remain intact, despite AT stump failure at loads of 241.5 ± 82.2 N and 348.8 ± 124.9 N for FHL and PB transfer reconstructions, respectively. In essence, it does not appear as though tensile failure of the transferred portion of either FHL or PB plays a role in the failure of AT reconstructions with these local tendon transfers. The fact that the AT reconstructions with the PB tendon failed at statistically significantly higher loads than did those wherein FHL was used may be related to the relationship of the direction of the fibers of the AT relative to the force and direction of the pull of the transferred tendon. However, we were not able to definitively determine why this was observed in the current experiment. Finni et al (25) have reported the peak in vivo force in the AT during walking to be 1430 N. This value is substantially greater than the failure loads observed in the cadaveric models that we tested and suggests that either the portion of the AT distal to the proximal slot, or the portion proximal to the distal slot, created for transfer of either FHL or PB, is the weakest link in the reconstruction models.

Based on the results obtained with our cadaveric experimental model, therefore, we feel that surgeons using local transfer of either the FHL or PB for repair of the chronically ruptured AT should consider reinforcing the stumps of the AT in an effort to prevent the transferred tendon from pulling out. Furthermore, the stiffness of the repair was 14.0 ± 3.8 N/mm and 16.5 ± 6.3 N/mm for the FHL and PB constructs, respectively, and these values are considerably lower than those reported for intact AT, FHL, or PB tendons (24). Therefore, it appears as though the addition of the locally transferred and sutured tendon grafts does not effect a construct stiffness that is near that of intact, normal AT; hence, the repair is unlikely to be able to resist similar tensile loads until an adequate period of time has gone by and the tendon has had time to remodel and become stronger with healing. Careful postoperative management with nonweightbearing and immobilization, therefore, is likely to be an important adjunct in the effort to achieve a satisfactory result in the clinical realm.

As with all in vitro investigations, our study conveys certain limitations that probably influence the clinical meaning of our results. We used macroscopically healthy ATs in our tests. In clinical practice, the AT stumps associated with neglected ruptures are likely to be atrophic and more degenerated (26, 27) and probably of inferior mechanical strength than those used in our cadaveric model. On the other hand, the specimens used in our investigation were harvested from cadavers of humans that were considerably older than the age of the typical patient sustaining an acute AT rupture or that of most patients dealing with chronic ruptures of the AT. It is likely that both of these biases may have neutralized one another, to some degree, in our investigation. Moreover, the human cadaver model used in this study only allowed the biomechanical testing of the reconstruction to be undertaken immediately after the repair and freezing of the proximal clamp. The construct did not take into consideration biotransformation of the reconstruction related to healing; hence, our model probably produced results that would be relatively weaker than those observed in the clinical realm (assuming that the patient underwent a satisfactory postoperative course). Therefore, on the basis of our data, no conclusions can be drawn regarding the possible functional outcome, longevity, or healing of the construct in vivo. Finally, our sample size of n = 8 per group was small, and this may have prevented us from identifying statistically significant differences in regard to stiffness, energy to failure, and mode of failure, should such differences actually exist. A post hoc power analysis revealed that a sample size of N >60 would have been required to detect statistically significant differences between the groups at $\alpha = 0.05$ and $\beta = 0.8$. At our institution, it is unrealistic to accrue a sample size of such magnitude because of difficulties related to obtaining cadaveric donor tissues for biomechanical testing.

In conclusion, based on the analysis of the biomechanical data obtained in this investigation, the use of either FHL or PB local tendon transfer for reconstruction of AT ruptures performs similarly in regard to stiffness, energy to failure, and mode of failure. The PB transfer displayed a higher load to failure than did use of FHL, and this difference was statistically significant, although it may not be clinically significant. Efforts toward reinforcing the integrity of the stumps of the AT to resist pullout of the transferred tendon may improve the biomechanical function of local transfer of either FHL or PB for reconstruction of the AT. Finally, the information gained from this investigation may be useful in the development of randomized, controlled trials comparing the use of FHL and PB local tendon transfers for repair of the chronically ruptured AT.

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