Effect of Knee Flexion Angle on Achilles Tendon Force and Ankle Joint Plantarflexion Moment During Passive Dorsiflexion

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Early mobilization exercises are advocated following Achilles tendon (AT) repair, but forces on the repair during passive range of motion are unknown. The extent to which these forces change with flexion of the knee is also not known. Estimated AT forces were measured using 3 models: cadaveric, uninjured subjects, and in both legs of subjects 6 weeks following unilateral AT repair. For cadaveric testing, estimated AT force was recorded using a force transducer while cycling the ankle from 10° plantarflexion to maximum dorsiflexion at 3 different knee flexion angles (0°, 45°, and 90°). For in vivo testing, subjects were seated in an isokinetic dynamometer, and their ankles passively cycled from plantarflexion to dorsiflexion with the knee extended and flexed 50°. Passive plantarflexion moment recorded by the dynamometer was converted to AT force by estimating the AT moment arm. In the cadaveric model, knee flexion reduced estimated AT forces during dorsiflexion by more than 40% (P < .036). In vivo testing showed that estimated AT force was reduced in knee flexion in healthy subjects (P < .001) and in the uninvolved leg AT repair subjects (P = .021), but not in the AT repaired leg (P = .387). Normal AT showed a marked reduction in estimated AT force with knee flexion which was not present in repaired AT. This could be because of elongation of the repair, causing more slack in the tendon that would need to be taken up before force transmission occurs. ACFAS Level of Clinical Evidence: 4. (The Journal of Foot & Ankle Surgery 47(1):34–39, 2008)

Key Words: Achilles tendon, repair, tension, passive dorsiflexion

The goal of early passive mobilization following Achilles tendon (AT) repair is to promote tendon healing and to avoid motion loss. Biomechanical studies have shown that mobilization during healing improves tensile strength and tendon vascularity (1–3). Clinically, patients managed with early mobilization after Achilles tendon repair had shorter rehabilitation time and shorter return-to-sport time versus patients who were immobilized (4, 5).

Previous research has shown that the Achilles tendon undergoes significant changes in length during passive dorsiflexion of the ankle (6). Herbert et al (7) demonstrated that most of the strain imposed by passive dorsiflexion was absorbed by the tendon. Examination of their data on muscle tendon unit and medial gastrocnemious fascicle length changes showed that the muscle tendon unit elongated by approximately 6 mm from 10° to 20° of dorsiflexion. This elongation translates into a considerable amount of force being transmitted through the Achilles tendon. However, the magnitude of this force is not known.

Commonly used Achilles tendon repair techniques have been shown to fail at forces ranging from 45 to 250 N (4, 8–11). The strongest reported techniques are the "triple bundle technique" failing at 453 N (12) and a 4-strand Krakow repair with epitendinous augmentation failing at 323 N (13). However, these augmented repair techniques are not widely used. Although early mobilization exercises are advocated following repair, the magnitude of the force transmitted through the Achilles tendon during passive range of motion (ROM) must not exceed the failure strength of the repair.

Because the gastrocnemius is a bi-articulate muscle (ie, crosses both the ankle and the knee) it may be possible to reduce Achilles tendon forces during passive dorsiflexion exercises to a safe range by simply flexing the knee. This would give the patient the benefits of early mobilization and

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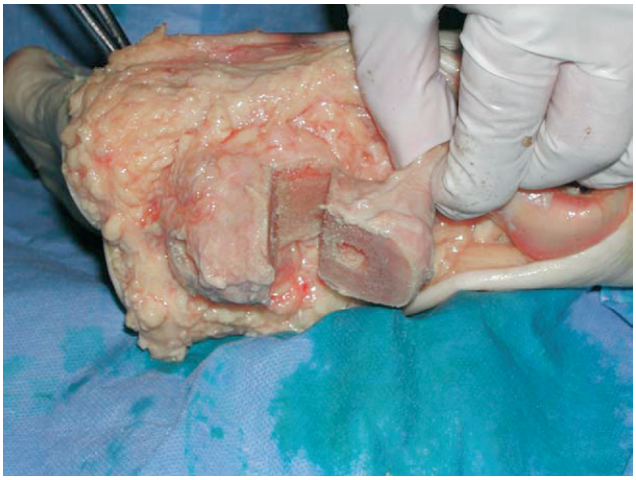

FIGURE 1 Calcaneal osteotomy with Achilles tendon insertion intact.

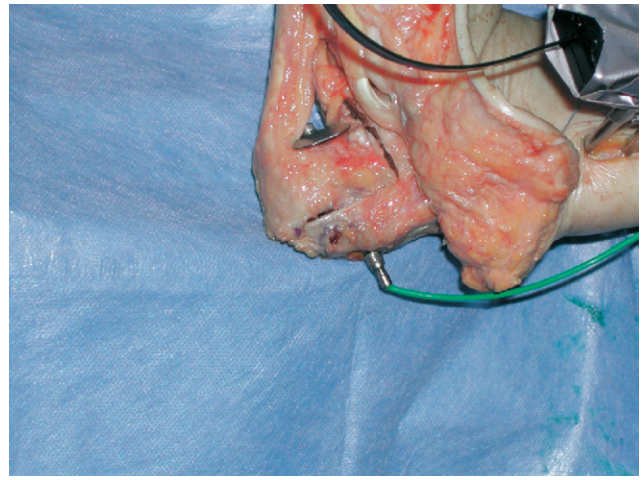

FIGURE 2 Calcaneal bone block in anatomic position with the force transducer attached through the drill hole to the superior surface.

not expose the repair site to potentially damaging loads. The extent to which estimated Achilles forces can be decreased by knee flexion during passive range of motion (ROM) exercises has not previously been examined. The goal of this study was to determine the effect of knee flexion angle on estimated Achilles tendon force during passive dorsiflexion.

Methods

The effect of knee flexion on Achilles tendon forces was examined using both cadaveric and in vivo testing.

Cadaveric Testing

A total of 7 lower extremities were used for cadaveric testing. A calcaneal osteotomy was made to provide a bone block with the Achilles tendon insertion intact (Figure 1). The calcaneal bone block was maintained in anatomic position by attaching it to a uniaxial force transducer fixed to the superior surface of the remaining intact calcaneous (Figure 2). An electrogoniometer was attached to the ankle. The proximal femur was clamped and the knee joint was set at each of 3 knee flexion angles (0°, 45°, or 90°) using a standard goniometer. At each knee flexion angle, the foot was manually cycled from full plantarflexion to full dorsiflexion 5 times. The force transmitted from the Achilles tendon to the calcaneal bone block and ankle angle were recorded continuously. The average force from the 5 cycles at each knee flexion angle was computed for 10° plantarflexion, neutral, 10° dorsiflexion, and peak dorsiflexion (approximately 20°).

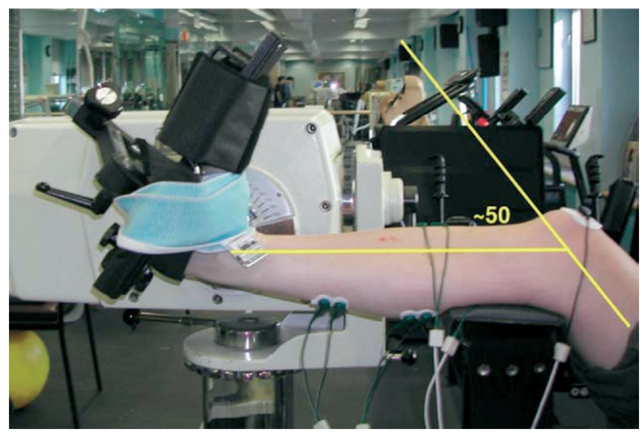

FIGURE 3 Subject seated at the dynamometer with the knee flexed to appromimately 50 degrees. The head of the dynamometer was aligned with the lateral malleolus. Passive plantarflexion torque was measure as the ankle was moved through the range of motion.

In Vivo Testing

Passive plantarflexion moment at the ankle was measured bilaterally using an isokinetic dynamometer in 23 subjects (age 33 ± 5 years): 12 healthy subjects (control group: 6 men, 6 women) and 11 patients with Achilles tendon repair (AT repair group: 10 men, 1 woman). Patients were tested within 6 weeks of surgery and had achieved at least 10° of passive dorsiflexion. Subjects were seated with the knee either in full extension or flexed to 50°. The axis of rotation of the dynamometer was aligned with the lateral malleolus (Figure 3). The dynamometer passively moved the ankle from full plantarflexion to full dorsiflexion at 5° per second. Two full cycles of motion were performed at each knee flexion angle. Joint moment and ROM were recorded continuously. To en-

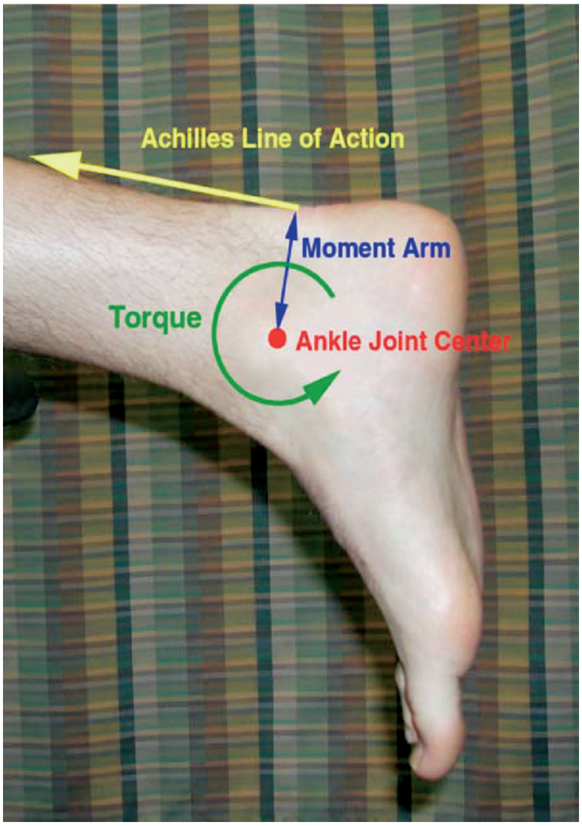

FIGURE 4 An estimate of the tension in the Achilles tendon was made by dividing the plantarflexion torque measured with the dynamometer by the moment arm from the malleolus to the line of action of the Achilles tendon.

sure that the subjects were fully relaxed, muscle activity was monitored during each trial with surface electrodes placed over the soleus, medial, and lateral gastrocnemius and the anterior tibialis. Passive plantarflexion moment (resistance to dorsiflexion motion) was recorded at 10° plantarflexion, neutral, 10° dorsiflexion, and 20° dorsiflexion at both knee flexion angles in healthy subjects. As some subjects with Achilles tendon repairs felt discomfort at 20° dorsiflexion, measurements in this group are only reported to 10° dorsiflexion. Moment values were divided by the estimated Achilles tendon moment arm to provide an estimate of Achilles tendon force. Moment arm was estimated by averaging the perpendicular distances from the Achilles tendon to the medial and lateral malleoli with the ankle in the neutral position (Figure 4).

Statistics

The effect of knee flexion angle on estimated Achilles tendon force was examined in the cadaveric model and the in vivo experiment (healthy control group) using repeated measures analysis of variance (knee angle by ankle angle). A second analysis of variance (side by knee angle by ankle angle) was performed to assess the effect of these factors on estimated Achilles tension in the AT repair group. Post hoc *t* tests were used to compare estimated Achilles tension measurements where a main effect or interaction was found. *P* less than .05 was considered significant.

Results

Cadaveric Testing

There was a significant effect of knee flexion angle on estimated Achilles tendon force ($P = .036$). When compared to the knee-extended position, knee flexion to 45° reduced the Achilles force by 70% at 10° of dorsiflexion ($P = .037$) and by 40% at peak dorsiflexion ($P < .001$) (Figure 5). Further knee flexion to 90° did not decrease estimated Achilles force at 10° dorsiflexion. However, at peak dorsiflexion, estimated Achilles force was reduced to 60% of the force with knee in full extension ($P = .01$ compared to 45°).

In Vivo Testing

In the control group, knee flexion significantly reduced estimated Achilles forces from 70.6 N to 17.8 N at neutral (73%, $P < .001$), from 183.2 N to 83.4 N at 10° of dorsiflexion (54%, $P < .001$) and from 401.8 N to 215.5 N at 20° of dorsiflexion (46%, $P < .001$) (Figure 6). For the AT repair group, there was no difference in estimated Achilles tension between the AT repaired limb and noninjured side ($P = .571$). An effect of knee flexion on Achilles force was apparent on the noninjured side ($P = .021$) but not on the AT repaired limb ($P = .387$) (Figure 7). On the noninjured side, estimated Achilles forces were reduced 45% at neutral (63.5 N to 34.9 N, $P = .034$) and 36% at 10° of dorsiflexion (154.5 N to 98.6 N, $P = .013$) with the knee flexed (Table 1). In the AT repaired limb, the nonsignificant differences in estimated Achilles forces between full extension and 50° knee flexion were 18% at neutral (47.5 N to 38.7 N, $P = .481$) and 17% at 10° of dorsiflexion (129.8 N to 107.3 N, $P = .365$) (Table 1).

Discussion

Cadaveric and in vivo testing in the control group indicated that with the knee in full extension the estimated passive AT forces may exceed the failure strength of some repairs when the ankle is dorsiflexed to 10°. However, when the knee was flexed to 45° to 50°, the passive forces in dorsiflexion appeared to be in a safe range. This response was not evident in the AT repaired limb as there was no difference in estimated AT force between the knee-extended and knee-flexed conditions.

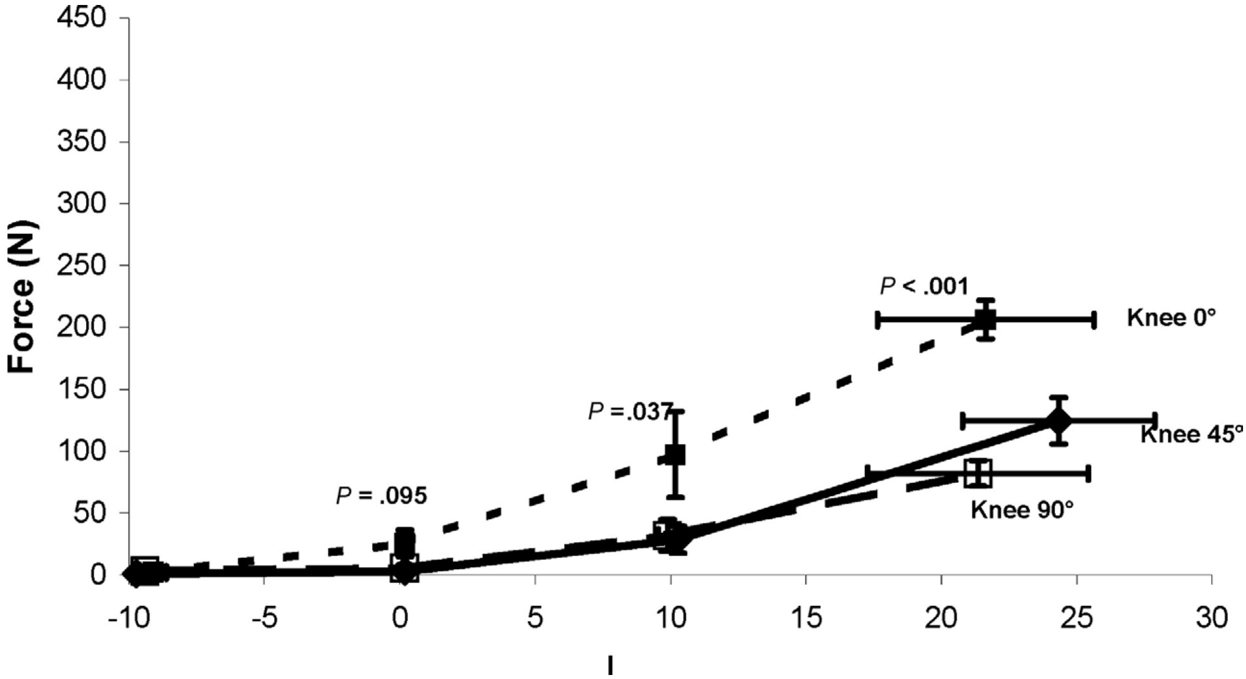

FIGURE 5 Mean and standard error for the Achilles tension measured in the cadaveric specimens. Tension was significantly reduced when the knee was flexed to 45 degrees compared to full extension (P = 0.036). Flexing the knee beyond 45 degrees did not further reduce tension in the Achilles tendon.

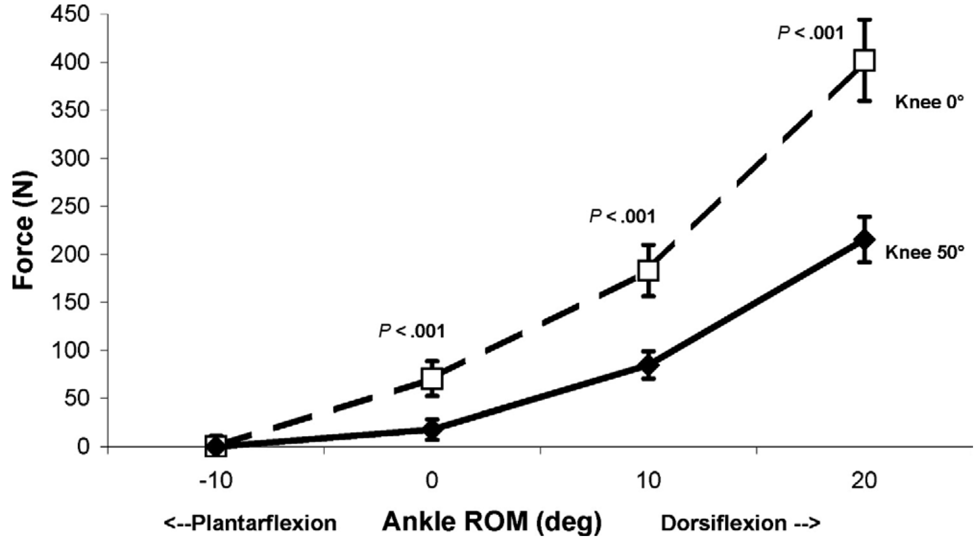

FIGURE 6 Mean and standard error for Achilles tension measured in the healthy subject group. Similar to the cadaveric data, flexing the knee to 50 degrees reduced tension in the Achilles tendon throughout the range of motion (P = 0.001).

That AT tension on the injured side was not significantly different in both the knee-flexed and knee-extended conditions could be attributed to tendon lengthening or increased tendon compliance following repair. Increased tendon compliance would have reduced Achilles tendon tension values in both the extended and flexed knee conditions. However, with the knee flexed, tension values at neutral and 10° of dorsiflexion were greater in the AT repaired limb compared to the noninjured limb. The reduction, albeit nonsignificant, in estimated Achilles tension observed only in the extended knee condition seems to indicate that tendon elongation may be the main contributor to reduced tension in the AT repaired limb. Because of the additional length in the repaired tendon, greater passive stretch would need to occur before a

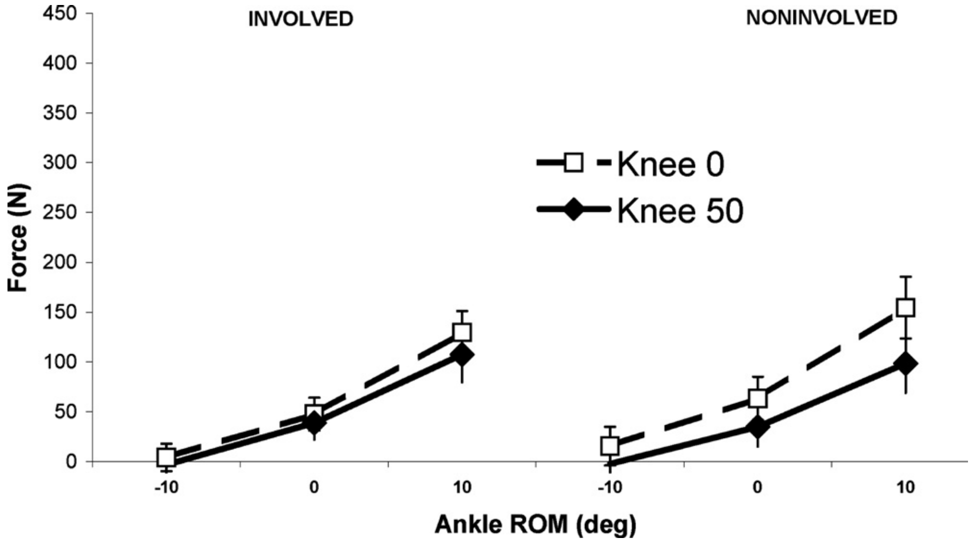

FIGURE 7 Achilles tendon tension measured in both the involved and noninvolved side of the patient group. In the noninvolved side, Achilles tension was reduced with the knee flexed (P = 0.021). However, no difference in tension was observed in the involved side when the knee was flexed (P = 0.387).

TABLE 1 Estimated Achilles tendon tension (N, mean [SD]) in the AT-repaired group

	10° Plantarflexion	Neutral	10° Dorsiflexion
AT-repaired side			
Knee extended	4.2 (13.8)	47.5 (16.6)	129.8 (21.3)
Knee flexed	−3.1 (14.7)	38.7 (16.8)	107.3 (27.7)
Noninjured side			
Knee extended	15.5 (19.3)	63.5 (21.6)	154.5 (31.0)
Knee flexed*	−2.3 (17.3)	34.9 (19.9)	98.6 (29.7)

Abbreviation: AT, Achilles tendon.

*Significantly different from Knee-extended condition (*P* = .013).

moment is generated about the joint. It is possible that a greater range of motion may have revealed a significant increase in estimated Achilles tension at angles above 10° of dorsiflexion in the AT repaired limb. However, passive dorsiflexion was restricted to 10° out of concern for patient comfort and to not damage the repair.

Elongation following Achilles repair has been reported in patients who followed an early motion regimen. Mortensen et al (4) reported a median separation of 9 mm in patients managed with early motion at 6-week follow-up. At 12-week follow-up, this increased to 11 mm. Patients who were immobilized had 5 mm of separation at the 6-week follow-up and 9 mm at 12 weeks. Despite the larger amount of separation in the tendon ends, the early mobilization group had shorter rehabilitation time and returned to sport sooner. Kangas et al (14) observed that patients managed with early mobilization had less separation than patients who were immobilized. Further, those patients with less elongation had better overall clinical outcomes. While both studies reported better outcomes for patients in the early mobilization groups, the outcome scores were based on strength measurements made with the ankle in neutral or a small amount of dorsiflexion. In these positions, the ankle musculature is at or near optimal length and the potentially negative effects of tendon separation may not be evident.

Mullaney et al (15) tested the isometric plantarflexion strength of 20 patients after Achilles tendon repair throughout the range of motion and found marked weakness in the AT-repaired limb at 10° plantarflexion and 20° plantarflexion. No strength deficit was observed at neutral, 10° dorsiflexion or 20° dorsiflexion (where peak moment occurred). Further functional testing revealed that most patients could not perform a heel rise on a decline with the AT-repaired limb. The authors hypothesized that these deficits in end-range plantarflexion strength could be because of excessive tendon lengthening, which placed the plantarflexors at a mechanical disadvantage to produce sufficient force.

There are a few limitations in this experiment that warrant mention. First, the AT tension was not directly measured in the in vivo portion of the experiment. Passive plantarflexion moment was measured as the ankle was cycled from plantarflexion to dorsiflexion and AT tension was calculated after measuring the AT moment arm with the ankle at neutral. While there are various techniques of directly measuring AT tension (eg, buckle transducers, fiber-optic sensors), the methods used in the current experiment seemed to be the most practical and, more importantly, noninvasive. Self and Paine (16) used a similar technique to measure AT forces during drop-landings. Using inverse dynamic techniques, the authors measured ankle plantarflexion moments during landing. Then, using an estimation of AT moment arm at each ankle angle, they approximated AT force.

A second limitation of this experiment was that the AT moment arm was assumed to be constant over the ROM. Rugg et al (17) measured AT moment arm as a function of ankle angle using magnetic resonance images (MRI) and found only a 10% change in AT moment arm over the ROM used in the in vivo portion of this study (10° plantarflexion to 20° dorsiflexion). While small changes in the AT moment arm may have led to a small amount of error in the estimated AT forces, any uncertainty in the measurements will affect the data from each subject in a similar manner. The main concern of this experiment was to measure the change in AT forces when the knee was flexed.

Finally, the position of the force transducer in the cadaveric experiment may not have been exactly in line with the Achilles tendon force. Depending on the relationship between the transducer and the Achilles tendon line-of-pull, the actual tension in the Achilles tendon may have been over- or underestimated. While there was uncertainty in the forces measured using this technique, the main goal of the experiment was to examine the change in Achilles tension as the knee is flexed. Achilles tension estimates were compared at each knee-flexion angle within each specimen. Therefore, the uncertainty due to transducer placement was controlled for in each specimen.

In conclusion, in the normal intact Achilles tendon, forces during passive dorsiflexion were substantially reduced by flexing the knee to 45° to 50°. However, in repaired Achilles tendons this effect of knee flexion was not apparent. This may be further evidence of tendon elongation and increased compliance following surgery. While the benefits of early mobilization regimens have been well documented, these protocols may contribute to elongation of the repair by stressing the healing tendon. Therefore, to reduce these potential effects and to protect the repair, it is recommended that early mobilization exercises be performed with the knee flexed and to not exceed neutral ankle position in the range of motion. Future work in this area should prospectively examine whether early mobilization exercises performed in this manner have an effect on tendon elongation and/or compliance.

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