Gastrocnemius fascicles are shorter and more pennate throughout the first month following acute Achilles tendon rupture

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The purpose of this study was to characterize the short-term effects of Achilles tendon ruptures on medial gastrocnemius. We hypothesized that the fascicles of the medial gastrocnemius muscle of the injured Achilles tendon would be shorter and more pennate immediately following the injury and would persist throughout 4 weeks post-injury. B-mode longitudinal ultrasound images of the medial gastrocnemius were acquired in 10 adults who suffered acute Achilles tendon ruptures and were treated non-operatively. Ultrasound images were acquired during the initial clinical visit following injury as well as two and four weeks following this initial clinical visit. Resting muscle structure was characterized by measuring fascicle length, pennation angle, muscle thickness, and muscle echo intensity in both the injured and contralateral (control) limbs. Fascicle length was 15% shorter ($P <$ 0.001) and pennation angle was 21% greater ($P <$ 0.001) in the injured muscle compared to the uninjured (control) muscle at the presentation of injury (week 0). These differences in fascicle length persisted through 4 weeks after injury ($P <$ 0.002) and pennation angle returned to pre-injury levels. Muscle thickness changes were not detected at any of the post-injury visits (difference < 4%, $P >$ 0.026). Echo intensity of the injured limb was 8% lower at the presentation of the injury but was not different compared to the contralateral muscle at 2 and 4 weeks post injury. Our results suggest that Achilles tendon ruptures elicit rapid changes in the configuration of the medial gastrocnemius, which may explain long-term functional deficits.

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Abstract

The purpose of this study was to characterize the short-term effects of Achilles tendon ruptures on medial gastrocnemius. We hypothesized that the fascicles of the medial gastrocnemius muscle of the injured Achilles tendon would be shorter and more pennate immediately following the injury and would persist throughout 4 weeks post-injury. B-mode longitudinal ultrasound images of the medial gastrocnemius were acquired in 10 adults who suffered acute Achilles tendon ruptures and were treated non-operatively. Ultrasound images were acquired during the initial clinical visit following injury as well as two and four weeks following this initial clinical visit. Resting muscle structure was characterized by measuring fascicle length, pennation angle, muscle thickness, and muscle echo intensity in both the injured and contralateral (control) limbs. Fascicle length was 15% shorter ($P < 0.001$) and pennation angle was 21% greater ($P < 0.001$) in the injured muscle compared to the uninjured (control) muscle at the presentation of injury (week 0). These differences in fascicle length persisted through 4 weeks after injury ($P < 0.002$) and pennation angle returned to pre-injury levels. Muscle thickness changes were not detected at any of the post-injury visits (difference < 4%, $P > 0.026$). Echo intensity of the injured limb was 8% lower at the presentation of the injury but was not different compared to the contralateral muscle at 2 and 4 weeks post injury. Our results suggest that Achilles tendon ruptures elicit rapid changes in the configuration of the medial gastrocnemius, which may explain long-term functional deficits.

Introduction

The incidence of Achilles tendon ruptures has increased 10-fold over the last three decades, disproportionally affecting athletic adults who participate in sports requiring sudden acceleration and jumping (Lantto et al., 2015). This well-documented increase in the prevalence of acute Achilles tendon ruptures (Nyyssönen, Lüthje & Kröger, 2008; Huttunen et al., 2014; Lantto et al., 2015) is most likely explained by the recent rise in sports participation amongst aging adults (Huttunen et al., 2014). While advances in rehabilitation protocols have improved outcomes in patients treated either operatively or non-operatively (Willits et al., 2010), approximately one out of five patients without other complications are unable to return to their previous levels of athletic participation (Zellers, Carmont & Silbernagel, 2016) and two out of three have long-term functional deficits (Brorsson et al., 2017).

Deficits in plantarflexion function of the affected limb play a large role in preventing return to pre-injury levels of activity (Olsson et al., 2011) and have been shown to persist as far out as 14-years following injury (Heikkinen et al., 2016; Brorsson et al., 2018). Clinically, these deficits present as resting ankle angles that are less plantarflexed (Zellers, Carmont & Silbernagel, 2018), reduced heel-raise height (Silbernagel, Steele & Manal, 2012; Brorsson et al., 2017), and 10-20% reductions in plantarflexion strength (Leppilahti et al., 2000; Pajala et al., 2009; Heikkinen et al., 2016). Tendon elongation and plantarflexor muscle atrophy have both been associated with these reductions in function (Mullaney et al., 2006; Silbernagel, Steele & Manal, 2012; Heikkinen et al., 2017a). Decreased resting tension in the muscle-tendon unit stimulates sarcomere subtraction in small animals (Williams & Goldspink, 1978; Williams, 1990), effectively restoring the resting tension in the muscle. Both increased tendon length and decreased muscle fascicle length have been shown to negatively affect single-leg heel raise performance in computational simulations (Baxter, Farber & Hast, 2018).

55   Plantarflexor function is governed by muscle-tendon structure. Although isometric
56 strength is a commonly measured metric of patient function and correlates with muscle size and
57 leverage (Baxter & Piazza, 2014), athletics require active plantarflexor shortening to generate
58 ankle power (Lee & Piazza, 2009). Longer muscle fascicles generate greater power during
59 isokinetic contractions (Drazan, Hullfish & Baxter, 2019b), which is beneficial for activities like
60 sprinting (Lee & Piazza, 2009). Targeted training can increase muscle fascicle length (Salzano et
61 al., 2018), effectively increasing power potential. Although muscle structure has been linked to
62 function in many populations, shorter muscle fascicles have only been reported in a single case
63 report of a patient with poor outcomes following an Achilles tendon rupture (Baxter, Hullfish &
64 Chao, 2018).

65   Sudden changes in muscle-tendon tension, either induced through joint immobilization
66 (Williams & Goldspink, 1978; Williams, 1990) or changes in muscle leverage (Burkholder &
67 Lieber, 1998; Koh & Herzog, 1998), stimulate changes in muscle fascicle length within weeks.
68 While a previous report documented muscle remodeling 3 to 6 months following acute Achilles
69 tendon ruptures (Peng et al., 2017), the response to an immediate loss of muscle-tendon tension
70 caused by Achilles tendon ruptures has not been prospectively studied in a patient cohort. Other
71 studies have found that 3-weeks of immobilization stimulates decreases in muscle strength by as
72 much as one-half in humans (Hortobágyi et al., 2000) and muscle remodeling characterized by a
73 25% decrease in serial sarcomere count (Williams & Goldspink, 1978).

74   Therefore, the purpose of this study was to quantify the immediate structural changes to
75 the medial gastrocnemius in patients who suffered acute Achilles tendon ruptures and were
76 treated non-operatively. We decided to study the medial gastrocnemius muscle because our
77 previous work found large changes in its structure that explained long-term functional deficits
78 (Baxter, Hullfish & Chao, 2018). We hypothesized that the medial gastrocnemius muscle would
79 have shorter and more pennate fascicles immediately following an acute Achilles tendon rupture
80 and these changes would persist throughout 4 weeks post-injury. Based on previous reports
81 (Williams & Goldspink, 1978; Hortobágyi et al., 2000), we expected that changes in muscle
82 structure following acute Achilles tendon rupture should be detected within the first 4 weeks
83 following injury.

Methods

Study Design

86   Ten adults (9 males, Age: 44 ± 12; BMI: 28.6 ± 6.5) who suffered acute Achilles tendon
87 ruptures (7 suffered during sports) and were treated non-operatively by a fellowship trained foot
88 and ankle surgeon and provided written-informed consent in this study approved by the
89 University of Pennsylvania IRB (828374). All patients were recruited from the clinics of the
90 Department of Orthopaedic Surgery at the Penn Medicine and met several inclusion criteria:
91 patient was between 18 and 65 years old, elected to be treated non-operatively for acute Achilles
92 tendon rupture within 2 weeks of injury. Patients were not enrolled in this study if they met any
93 of our exclusion criteria: excessive weight (BMI < 50) or concomitant lower extremity injuries.
94 These patients were enrolled in a 1-year prospective study aimed at linking muscle remodeling
95 with patient outcomes and function. To first determine how muscle structure changes in the first
96 month following injury, we analyzed the imaging data of all patients enrolled in this study at the
97 time of analysis. We acquired ultrasound images of the medial gastrocnemius during three
98 clinical visits (**Figure 1**): time of injury when patients were placed in a cast (week 0); time of

99   cast removal when patients were transitioned into partial weight bearing in a walking boot (week
100   2); and 2 weeks after transitioning into boot use (week 4). Patients were enrolled in this study
101   within 10 days of suffering the injury (4.5 ± 3.5 days), at which the week 0 images were
102   acquired. We imaged both the affected and contralateral limbs at each time point to determine
103   changes in resting muscle structure. Resting structure of the muscle was characterized by the
104   length and pennation angle of the constituent fascicles as well as the thickness of the muscle
105   belly. We also performed a secondary analysis of average muscle echo intensity to characterize
106   'muscle quality', which may be a surrogate measure of muscle remodeling and atrophy
107   (Fukumoto et al., 2012).

108   ## Image Acquisition
109   Longitudinal images of the medial gastrocnemius (**Figure 2**) were acquired while
110   patients lay prone on a treatment table with their feet and ankles supported by the edge of the
111   table in plantarflexion and kept in the same position for all imaging sessions. At the beginning of
112   each imaging session, patients lay on the treatment table with their ankles resting off the edge of
113   the table (Zellers, Carmont & Silbernagel, 2018). We have used this resting angle previously to
114   longitudinally study Achilles tendon structure (Hagan et al., 2018). In order to minimize the
115   loads applied to the healing tendon, the patients slid proximally on the table to support both
116   ankles in the resting position of the uninjured limb. Continuous B-mode ultrasound images of the
117   medial gastrocnemius were acquired by a single investigator using an 8 MHz ultrasound
118   transducer with a 6 cm scanning width (LV7.5/60/128Z-2, SmartUs, TELEMED). We followed
119   the guidelines for reliably imaging medial gastrocnemius muscles outlined by Bolsterlee et al.
120   (2016). Briefly, we positioned the probe half way between the muscle-tendon junction and crease
121   of the knee in the central portion of the muscle belly and aligned with the fascicles to ensure that
122   the muscle fascicles lie in the image plane. During pilot testing, we identified scanning
123   parameters (scan parameters: Dynamic Range: 72 dB; Frequency: 8 MHz; Gain: 47 dB) that
124   produced high-contrast images and held them constant for all patients and scanning sessions. We
125   also confirmed during pilot testing that imaging along the midline of the muscle belly produced
126   similar measurements of fascicle length and pennation angle. Specifically, imaging the central,
127   medial, lateral, medial-central, and latera-central regions of the muscle resulted in similar
128   measurements of fascicle length (standard deviation < 1.5mm) and pennation angle (standard
129   deviation < 1 degree).

130   All images were acquired by the same investigator and saved as digital videos to be
131   processed later by the same investigator. During each imaging session, the investigator pressed a
132   foot switch when the ultrasound image produced fascicles that were in plane in order to analyze
133   these specific frames during post-processing. These individual frames from the continuous
134   imaging were exported as still images to be processed for muscle structure. In order to protect
135   the rupture, we acquired images with the foot fully supported in plantarflexion. During the first
136   study visit (week 0), the Achilles tendon did not transfer any load, which was confirmed by
137   moving the ankle joint while observing no change in muscle structure via real-time ultrasound
138   imaging. Because of this observation, we considered the first visit scans of the injured muscle,
139   which were acquired on average 4.5 days after injury, to accurately represent muscle structure
140   immediately following the rupture. To confirm that probe placement was repeatable between
141   sessions, we imaged the contralateral (control) muscle at each visit and found that these
142   measurements of muscle architecture had coefficients of variation of less than 10% and intra

143   class correlations greater than 0.84 (Supplemental Material). These metrics of reliability agree
144   with previous reports in the literature (Kwah et al., 2013).

Image Analysis

146   Resting fascicle length, pennation angle, muscle thickness, and muscle echo intensity
147   were quantified using custom written software (MATLAB 2017b, The MathWorks, Inc, Natick,
148   MA) (Baxter, Hullfish & Chao, 2018). We anonymized and randomized each image to ensure
149   that the investigator analyzing the images could not be biased. For each image, the investigator
150   identified the deep and superficial aponeuroses as well as a single fascicle (**Figure 2**). We
151   quantified fascicle length as the distance between the fascicle's insertions into the aponeuroses.
152   Pennation angle was determined to the be the angle between the fascicle and the deep
153   aponeuroses. Muscle thickness was calculated based on fascicle length and pennation angle
154   (**Equation 1**). During this analysis, we observed that many of the ultrasound images showed the
155   muscle to be of 'poor quality', which was visually apparent based on reduced contrast between
156   muscle fascicle and interstitial connective tissue (**Figure 2b**). Therefore, we calculated the mean
157   echo intensity between deep and superficial aponeuroses to quantify muscle quality. Because we
158   acquired all ultrasound images with the same scanning parameters, we used the raw echo
159   intensity values that ranged between 0 and 255. A previous study correlated muscle strength with
160   mean echo intensity and attributed this link between muscle form and function to increased
161   fibrous and adipose tissues within the muscle belly (Fukumoto et al., 2012).

162   ***Eq. 1****. thickness* $= l_{fascicle} \times \sin \theta_{pennation}$

Statistical Analysis

164   To test our hypothesis that resting muscle architecture would change following injury,
165   resting fascicle length, pennation angle, muscle thickness, and mean echo intensity at week 0, 2,
166   and 4 were each compared to against measurements of the contralateral muscle at each visit
167   using paired one-way t-tests. We adjusted for multiple comparisons using a Bonferroni
168   correction, which set the threshold for statistical significance to p = 0.05 / 3 = 0.0167, where 3 is
169   the number of comparisons for each variable of interest. When muscle structure parameters
170   differed from the control values, we calculated the Cohen's effect size (*d*). We performed an *a*
171   *priori* sample size calculation based on the variation of medial gastrocnemius fascicle length in
172   young adults (Baxter & Piazza, 2014) and determined that 10 patients would be able to detect a
173   10% decrease with desired statistical power of 0.8.

Results

175   Gastrocnemius muscle structure following an acute Achilles tendon rupture differed with
176   the healthy-contralateral muscle throughout the first four weeks following injury (**Figure 3**).
177   Fascicle length was 15% shorter (*d* = 1.7, *P* < 0.001) and pennation angle was 21% greater (*d* =
178   1.6, *P* < 0.001) at the presentation of injury (week 0). These differences in fascicle length
179   persisted throughout the 4 weeks after the injury (*d* > 1.6, *P* < 0.001) while pennation angle was
180   similar at week 2 (*d* = 0.9, *P* = 0.017) before returning to within 10% of the contralateral muscle
181   at week 4. Muscle thickness changes were not detected at any of the post-injury visits; however,
182   a 3 − 4% decrease in muscle thickness at weeks 2 and 4 approached our threshold for
183   significance when controlling for multiple comparisons (*d* = 0.7 − 0.8, *P* = 0.026 − 0.28). Muscle
184   quality, measured as mean echo intensity of the muscle belly, was 8% lower in the injured limb

185 immediately ($d = 0.9$, $P = 0.008$) and 11% lower 2 weeks following injury ($d = 1.5$, $P < 0.001$).
186 At week 4 muscle quality had returned to within 1% of the contralateral limb ($P = 0.393$).

Discussion

188 The purpose of this study was to quantify medial gastrocnemius structure following the
189 first month of acute Achilles tendon ruptures. Our findings support our hypothesis that the
190 gastrocnemius muscle fascicles of the affected side would demonstrate shorter length and greater
191 pennation angle than the contralateral control muscle. These changes appear to be a mechanical
192 response to a sudden loss of intra-muscular tension – typically present with an intact tendon
193 (Hug et al., 2013) – that likely stimulates biological remodeling of the serial sarcomeres
194 observed in immobilization studies (Williams & Goldspink, 1978). We confirmed that no load
195 was carried between the Achilles tendon and gastrocnemius following injury by manually
196 rotating the ankle while observing no change in muscle fascicle length or pennation angle via
197 real-time ultrasound imaging. Our report is the first to our knowledge to document
198 gastrocnemius remodeling within the first month following an Achilles tendon rupture.

199 Our measurements of medial gastrocnemius structure compared favorably with prior
200 reports. Due to the clinical constraints of these patients, we were required to image the muscle of
201 the injured side with the foot supported in maximal plantarflexion by a table. As expected, our
202 measurements of gastrocnemius structure were shorter and more pennate than compared to other
203 studies that have measured gastrocnemius structure at neutral ankle angle (Lee & Piazza, 2009;
204 Baxter & Piazza, 2014). Unlike these previous studies, we measured muscle architecture with the
205 ankle fully supported in plantarflexion to protect the healing tendon. As expected, our
206 measurements of fascicle length and pennation angle were similar to a previous report of
207 gastrocnemius structure in peak plantarflexion (Gao et al., 2009), which demonstrated a linear
208 decrease in fascicle length and increase in pennation angle with increasing plantarflexion angle.
209 We calculated muscle thickness using a single longitudinal scan of the muscle belly rather than a
210 transverse scan or multiple longitudinal scans at different locations. Using this imaging
211 approach, we detected a small (4%) decrease in muscle thickness at week 4 that approached
212 statistical significance ($P = 0.026$). This small decrease in muscle thickness was less than
213 previous reports of muscle atrophy at least 1 year following injury (Heikkinen et al., 2017a,b).
214 Our findings that resting fascicle length decreases following Achilles tendon rupture also
215 compare favorably with a previous report that found fascicle length decreases by 20% 3-6
216 months after Achilles tendon ruptures were surgically repaired (Peng et al., 2017). Decreases in
217 muscle quality have been associated with age-related muscle deterioration such as sarcopenia
218 (Fukumoto et al., 2012), but these changes have not been observed in muscle following tendon
219 rupture. Side to side differences in rectus femoris fascicle length, pennation angle, thickness, and
220 echo intensity have been reported to be less than 11% (Mangine et al., 2014). However, this
221 previous study quantified the muscle of elite basketball players that may have had greater muscle
222 structure asymmetry due to sport specific training and history.

223 Functional deficits are associated with elongated tendon and shorter muscle fascicles
224 following Achilles tendon rupture. Recent reports and our current findings document changes in
225 plantarflexor structure that occurs within the first weeks following rupture, persist through 3-6
226 months (Peng et al., 2017), and appear to lead to permanent muscle remodeling (Baxter, Hullfish
227 & Chao, 2018). Tendon elongation has been identified as a key clinical measure that explains
228 long-term deficits in function (Silbernagel, Steele & Manal, 2012; Brorsson et al., 2017). When

229   considered in this context, our current findings of shorter and more pennate gastrocnemius
230   fascicles immediately following Achilles tendon rupture indicate a coupled remodeling response
231   with the healing tendon.(Suydam et al., 2015) Imaging studies of the healing Achilles tendon
232   show continued tendon elongation (Nyström & Holmlund, 1983; Mortensen, Skov & Jensen,
233   1999; Kangas et al., 2007), which suggests that muscle-tendon adaptations continue for several
234   months following the injury. We hypothesize that the initial tendon injury mechanically unloads
235   the muscle that stimulates a rapid change in muscle structure in an attempt to restore the optimal
236   resting tension in the muscle-tendon unit (Williams & Goldspink, 1978), which potentially
237   triggers a positive feedback loop. Prospective research is needed to directly link the interaction
238   between tendon elongation and muscle remodeling. Understanding the progression of this
239   remodeling process is crucial for the treatment of tendon injuries and can be used to inform
240   clinical decisions as well as the prescription of rehabilitation protocols. Although tendon loading
241   is restricted during the first month following injury, shorter and more pennate muscle fascicles
242   may lead to increased muscle-tendon tension and drive additional tendon elongation (Kangas et
243   al., 2007).

244   In addition to our current findings that skeletal muscle architecture is sensitive to tendon
245   rupture, muscle fascicle length can also be affected by loading, pathology, surgical procedures,
246   and immobilization in both humans and animal models. High-acceleration training during
247   maturation in guinea fowl stimulates longer muscle fascicles that contain greater amounts of
248   sarcomeres in series (Salzano et al., 2018). Children with cerebral palsy have shorter
249   gastrocnemius fascicles that can be increased with surgical correction of the plantarflexor
250   contracture (Wren et al., 2010). Increasing the muscle shortening demands by surgically
251   releasing the ankle retinaculum elicits rapid sarcomere subtraction in both mice (Burkholder &
252   Lieber, 1998) and rabbits (Koh & Herzog, 1998). Immobilizing the ankle joint in plantarflexion
253   elicits muscle fiber remodeling, highlighted by a shorter optimal length and reduced sarcomeres
254   in series (Williams & Goldspink, 1978; Williams, 1990). Seminal work by Williams (Williams,
255   1990) demonstrates the importance of muscle tension on muscle length and joint range of motion
256   in the context of immobilization. Achilles tendon ruptures have been associated with muscle
257   atrophy (Rosso et al., 2013; Heikkinen et al., 2017a); however, we did not quantify any decreases
258   in muscle thickness throughout the 4 weeks following the injury. While our measurements of
259   pennation angle made during the first two weeks following injury demonstrate large increases in
260   pennation angle (effect size > 0.9), the 95% confidence intervals at 4 weeks suggests that the
261   muscle pennation angle decreased. These observations agree with previous reports that found no
262   difference in pennation angle at 6 months between the injured and uninjured sides (Peng et al.,
263   2017). This improvement in pennation angle may be due to increased weight bearing when
264   patients transition from the full-leg cast to the walking boot. However, additional research is
265   required to fully understand the tendon loading biomechanics during ambulation in these two
266   protective devices. While our study was not designed to quantify muscle volume, it is plausible
267   that atrophy did occur during our time points when considering a shorter muscle belly defined by
268   shorter and more pennate fascicles.

269   This study had several limitations, which should be considered when interpreting our
270   findings. We focused on the first 4 weeks following acute Achilles tendon rupture to characterize
271   structural changes to the skeletal muscle. While this timespan may appear short, previous
272   immobilization studies in both humans (Hortobágyi et al., 2000) and small animals (Williams &
273   Goldspink, 1978) have demonstrated that this time scale elicits detectable changes to both

274   muscle structure and function. We imaged the gastrocnemius muscle with both ankles supported
275   in their resting position and did not control this angle between test sessions. However, our
276   repeated imaging of the control limb suggests that this ankle angle was consistent because
277   measures of muscle structure of the control limb were similar between sessions. This study only
278   tested the effects of non-operatively treated Achilles tendon ruptures, which limits the
279   implications of our findings to that specific population of patients. Out of the 10 patients enrolled
280   in this study, only 1 was female, which is consistent with the four to one ratio of male to female
281   patients reported in the literature (Raikin, Garras & Krapchev, 2013). We did not perform muscle
282   biopsy or intramuscular sarcomere measurement (Sanchez et al., 2015); as such, this study was
283   not designed to establish whether optimal sarcomere length was preserved via sarcomere
284   subtraction or not. However, animal studies that imposed sudden changes in joint mechanics
285   demonstrates that rapid change in sarcomere number to preserve optimal sarcomere length
286   (Williams, 1990; Burkholder & Lieber, 1998; Koh & Herzog, 1998). Additionally, our
287   measurements of 'muscle quality' that were quantified by average echo intensity have been
288   described in the literature (Fukumoto et al., 2012) but should be investigated further to validate
289   this measurement. This qualitative decrease 'muscle quality' may have affected our manual
290   measurements of fascicle length and pennation angle. However, our group has demonstrated that
291   manual measurements of healthy muscle under passive and maximal contractions are highly
292   repeatable (Drazan, Hullfish & Baxter, 2019a), the latter having a similar appearance to patients
293   with injured Achilles tendon. We decided to image the medial gastrocnemius, which has longer
294   and less pennate fascicles than the soleus and generates tension in greater amounts of
295   plantarflexion (Hirata et al., 2015), which is critical for functional tasks such as heel raises. We
296   did not measure muscle structure prior to the injury, and therefore it possible that these structural
297   differences existed prior to the injury. However, muscle atrophy is well reported in this
298   population (Heikkinen et al., 2017a), suggesting that muscle structure was symmetrical prior to
299   injury. Controlled experiments using small animal models are needed to test the effects of pre-
300   injury muscle structure on post-injury remodeling.

301   These findings are a preliminary data set from a larger clinical cohort of patients that
302   were enrolled in an ongoing 1-year long prospective study. We are closely monitoring muscle
303   and tendon structure at each clinical visit. Once cleared for activity, we will test plantarflexor
304   strength and power in these patients using dynamometry and single-leg heel raises (Baxter &
305   Piazza, 2014; Baxter, Hullfish & Chao, 2018). Prior research also suggests that these structural
306   changes in muscle are permanent (Baxter, Hullfish & Chao, 2018) and the magnitude of these
307   changes may be predictive of long-term functional deficits (Silbernagel, Steele & Manal, 2012;
308   Baxter, Farber & Hast, 2018).

Conclusions

310   In summary, our findings demonstrate that the medial gastrocnemius muscle undergoes
311   rapid changes in configuration following an acute Achilles tendon rupture, which may explain
312   long-term functional deficits in many patients. While the mechanisms governing these changes
313   remain unclear, small animal studies suggest that perturbations in muscle-tendon tension
314   stimulate these changes. Future research should be focused on the effects of muscle-tendon
315   tension on muscle remodeling pathways.

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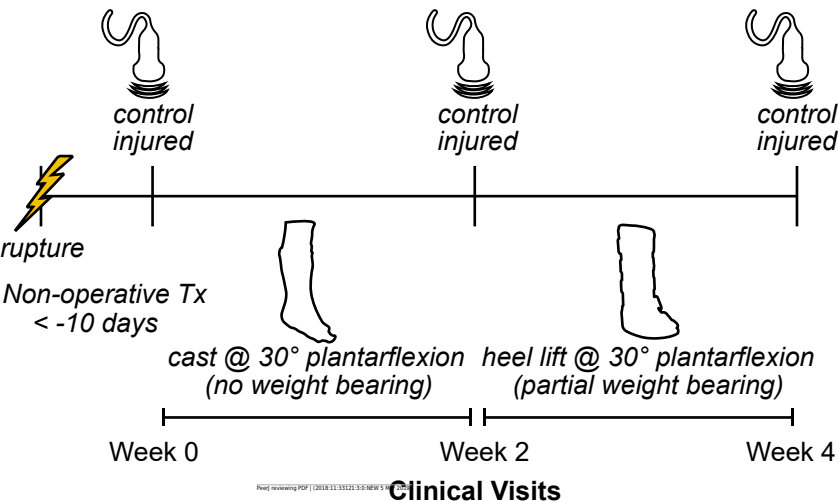
452

Study outline.

Patients who suffered acute Achilles tendon ruptures and received non-operative treatment were enrolled in this prospective study at their initial clinical visit (week 0). We measured the structure of the medial gastrocnemius muscle on both the injured and contralateral sides using ultrasound at each clinical visit (week 0, 2, and 4). At initial presentation, patients were placed in a plantarflexed cast and were instructed to avoid any weight bearing. At the two-week follow-up visit, the cast was removed and patients were placed in an orthopaedic boot with heel wedges to place the foot in approximately 30 degrees of plantarflexion. Patients were instructed to apply light pressure to the foot while ambulating with crutches.

Ultrasound Imaging - Medial Gastrocnemius Structure

Ultrasound imaging quantifying muscle structure.

Ultrasound images of the medial gastrocnemius were acquired and analyzed by the same investigator to quantify resting fascicle length, pennation angle, thickness, and muscle belly echogenicity. This figure shows a representative image of both the uninjured (A, control) and injured (B) sides. Fascicle length and pennation angle was analyzed by the same observer for all trials. Muscle thickness was calculated as the product of the fascicle length and sine of the pennation angle. During our initial analyses, we noticed that the injured limb displayed 'poor quality' muscle, as noted by a lack of contrast between the fascicles and interstitial connective tissue.

Medial Gastrocnemius Structure - Initial Presentation

Control

Injured

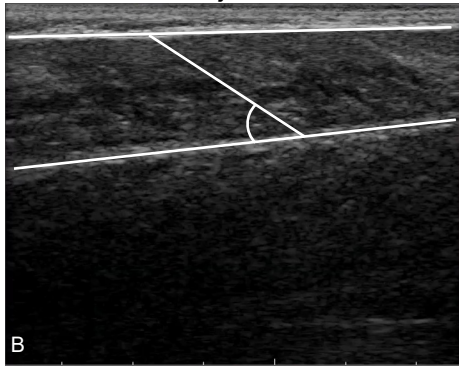
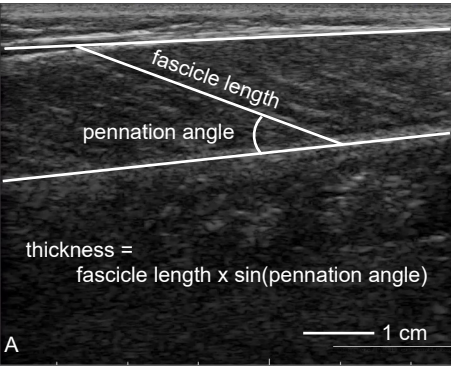
fascicle length

pennation angle

thickness =
fascicle length x sin(pennation angle)

1 cm

A

B

Muscle structure following Achilles tendon rupture.

Medial gastrocnemius structure following Achilles tendon rupture (*closed circles*) was compared to the contralateral muscle (control - crosses) at each time point. Resting fascicle length (A) decreased while pennation angle (B) increased in similar proportions, which explained the stable muscle belly thickness (C) following 4 weeks of injury. Muscle echogenicity (D) decreased by 8% at week 0 but returned to non-injured values at weeks 2 and 4. (* $P < 0.017$, dashed lines – 95% confidence intervals, d – Cohen's effect size, %Δ – percent change from control data, week 0 – N=10, week 2 – N=8, week 4 – N=10).