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Title:

Muscular Morphomechanical Characteristics After an Achilles Repair

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Abstract

Background:

The purpose of the study was to compare the morphomechanical and functional characteristics during maximal isometric, concentric, and eccentric contractions in the legs of patients that underwent unilateral Achilles tendon repair with those in their noninjured control legs.

Methods:

Twenty participants (median age = 38.2 years; range, 21.1-57.3 years) who underwent Achilles repair between 3 and 12 months ago were recruited with the following measures: (1) mechanical stiffness of the aponeurosis and (2) electromyography and medial gastrocnemius fascicle angle and length, standing muscle and tendon length, and height of heel rise with isometric contraction.

Results:

Compared to the noninjured legs, the repaired legs showed less resting fascicle length, standing muscle length, isometric plantarflexion torque, and heel raise distance (Ps ranged between .044 and <.001). During the concentric and eccentric phases of the raising and lowering test, the repaired legs demonstrated less fascicle length ($P \leqslant .028$) but greater tendinous tissue length (Ps ranged between .084 and <.001) and fascicle angle (Ps ranged between .247 and .008) and fewer change magnitudes of the fascicle length and tendinous tissue length ($P \leqslant .003$). The change magnitudes of the morphological characteristics showed correlations with the torque or distance.

Conclusion:

Selecting the appropriate surgical repair and rehabilitation for Achilles tendon ruptures is recommended for restoring the length and mechanical strength of the muscle-tendon unit of plantar-flexion muscles.

Level of Evidence:

Level III, comparative study.

Introduction

Deficits in plantarflexion strength or heel-raising test years after an Achilles rupture have attracted the attention of researchers and clinicians seeking to generate a comprehensive solution to the long-term ankle joint disability.4,5,28 Maximal performances during the tests are dependent on optimal muscle cross-sectional area, fascicle geometry (length and angle), stiffness, or length of the myotendinous unit.27 Previous studies have suggested that the causes of the deficits include muscle atrophy and Achilles tendon lengthening based on the associations found between (1) calf muscle size and plantarflexion strength and (2) the side-to-side difference in Achilles tendon length and the strength deficit after Achilles rupture repair.11,16,22 This is because a calf muscle with an Achilles rupture may show a shifted (Frank-Starling) length-tension relationship and force-generating range in a stretch-shortening contraction and, consequently, no maximization of muscular contraction.13,38 The morphomechanical changes relating to mechanical remodeling and morphogenetic adaptation of the myotendinous unit in the calf muscles after an Achilles rupture, such as reduced mechanical stiffness (ie, the resistance of the muscle aponeurosis or Achilles tendon to deformation under mechanical load), tendon lengthening, and alterations of fascicle geometry during contractions,30,36,39 theoretically reduce the change magnitude of the length of the myotendinous complex, leading to less effective storage and release of elastic potential energy and limiting the modulation of the fascicle geometry (length and angle).12,32

The elongation magnitude of tendinous tissues in healthy participants was previously reported to be larger with the ankle positioned in the plantar flexion position than in the dorsiflexion and neutral positions in evaluations of muscle fascicle shortening during isometric contractions in the medial gastrocnemius.9 Furthermore, the fascicle of the medial gastrocnemius muscle and the tendinous tissue in healthy participants were observed to become lengthened and shortened, respectively, in the dorsiflexion and plantarflexion phase of a toe-standing exercise.18 These findings collectively indicate that the tendinous tissue, by changing its length, eliminates slack in the muscle-tendon complex and attenuates the power input to the gastrocnemius muscle fascicles during contractions.32 The heel-raise height was found to differ significantly between the injured and uninjured sides at the 6- and 12-month evaluations in patients with an Achilles rupture who had received surgical or nonsurgical treatment.35 The heel raising involving concentric and eccentric contractions seems to be a validated test to measure the morphomechanical adaptation in the repaired leg within 1 year after the Achilles rupture. However, the fascicle-tendon geometry, elongation magnitude, and interactions between the fascicle and tendon during movements involving isometric, concentric, and eccentric muscle contractions after an Achilles tendon rupture have yet to be fully described.

The aims of this study were to compare the relevant morphomechanical characteristics, including the fascicle length and angle, length of the muscle-tendon unit, and length of the tendinous tissue during isometric contractions and dynamic heel-raising and -lowering exercises, as well as the mechanical stiffness of the proximal aponeurosis of the medial gastrocnemius muscle, in the legs of participants within 1 year of a unilateral Achilles repair. We hypothesized that when compared to the contralateral noninjured legs of the participants, the contracting repaired legs would exhibit significantly decreased fascicle lengths or greater pennation angles as well as decreased stiffness in the proximal aponeurosis of the medial gastrocnemius muscle. In addition, we hypothesized that the magnitude of the morphological changes in the medial gastrocnemius muscle or the stiffness of the muscle's proximal aponeurosis during the contractions would be less or would correlate with the plantarflexion torque or the range of the ankle in heel-raising and -lowering exercises.

Methods

Subjects

This study was approved by the institutional review boards of National Taiwan University Hospital and conducted from June 2015 to September 2017. Written informed consent was obtained from all participants prior to participation. There were 2 groups of participants: one that had surgery on 1 leg with a normal opposite side leg and another consisting of healthy participants with no surgery or history of Achilles problems. The methodologies involving ultrasound images, electromyography (EMG), and electrical or optical 2-dimensional motion have been reported in previous studies.6,16,30,40 The surgeons who treated the study participants consisted of 4 orthopedic surgeons who primarily use an open medial approach surgery combined with the Kessler suturing technique with an absorbable suture and end-to-end anastomosis to repair ruptured Achilles tendons. These surgeons' patients followed a 16-week rehabilitation protocol3,37 after such repairs and were invited to join the study for subject recruitment. The inclusion criteria for the injured participants were aged between 20 and 60 years and having had a unilateral Achilles repair within the past 3 to 12 months. Potential participants were excluded if they: (1) exhibited any positive signs or evidence of tendinopathy in their noninjured control leg as determined by physical examination24 or ultrasonographic screening29 with a 4 to 15 MHz broadband linear array transducer (T3300, BenQ, Taoyuan, Taiwan), (2) had a delayed surgery (>1 week) or were diagnosed with a sural nerve injury, or (3) did not complete the 16-week rehabilitation protocol with physiotherapists. All measurements were taken for both (ie, the repaired and noninjured) legs in the order of a block randomization scheme. There was a 10-minute interval of rest between the measurements for the 2 legs. For the healthy participant group, inclusion criteria were aged between 20 and 60 years with no prior lower extremity injury. These patients were excluded if the ultrasound or exam showed evidence of tendinopathy.24,29 The reliability measurements of the healthy participants were performed on their right legs (the dominant legs) and repeated within 1 week.

Isometric Measurement and Muscle Aponeurosis Stiffness

We measured the aponeurosis longitudinal strains as well as fascicle geometry changes of the medial gastrocnemius during the isometric contractions with the methodologies that have been described previously.30,40 A load cell (SLS410-Load Cell, Mettler-Toledo Pac Rim AG, Taipei, Taiwan) connected to a footplate was used to record voluntary isometric torque. Ankle position was assessed by continuous recording of the degree of ankle flexion by an electrogoniometer (Sharp Sensor S700, Measurand Inc, Fredericton, Canada), which was connected to an MP100 system (Biopac, Santa Barbara, CA) (same for the load cell) and sampled at 1200 Hz. The myoelectrical activities of the medial gastrocnemius and tibialis anterior were measured using wireless surface EMG recording electrodes (DTS, Noraxon, Scottsdale, AZ). Signals were amplified from the surface electrodes (impedance = 100 MΩ; gain = 500), band-pass filtered from 20 Hz to 500 Hz, and sampled at 1500 Hz with a common rejection ratio of 100 dB. Ultrasound measures performed with 4 to 15 MHz B-mode ultrasonography were taken first on the muscle belly of the medial gastrocnemius and medial to the EMG recording electrode. The ultrasonography was recorded using a 30 Hz camera (Sony DVD803, Toyko, Japan). Each participant was instructed to gradually increase the plantarflexion force in their foot from a relaxed status to the maximal voluntary isometric contraction (MVIC) within 5 seconds and then to progressively relax to complete relaxation. For synchronization, software containing simulating switching circuits written using LabVIEW 7.1 (National Instruments, Austin, TX) was used to add audio-electrical signals to the camera, EMG, and MP100 system at the beginning and end of each measurement. The pennation angle was defined as the angle between the echo of the deep aponeurosis and the interspaces among the fascicles of the medial gastrocnemius muscle.30 The fascicle length was calculated by dividing the thickness by the sine component of the pennation angle.21 Offline analyses included analyses of the change of the angle and length between the values at rest and at MVIC as well as an analysis of the length changes of the tendinous tissue (TT; free tendon and aponeurosis) as determined by subtracting the fascicle length multiplied by the cosine of the pennation angle at MVIC from the fascicle length multiplied by the cosine of the pennation angle at rest.8,14 The ultrasound transducer was then placed in the sagittal plane over the distal part of the muscle, with the myotendinous junction and a most identifiable cross-point from the fascicle and the proximal aponeurosis.25,30 Displacement digitalization of the junction was performed by the same examiner by using MATLAB 7.1 software (MathWorks, Natick, MA). Corrected displacements of the myotendinous junction and the proximal aponeurosis of the gastrocnemius on the ultrasonographic images along with adjusted plantarflexion and tendon force values of the corresponding ankle joints during the contraction phase were fitted with second-order polynomial functions.30 Stiffness in the aponeurosis was defined as the slope of the ascending phase of muscle contraction between 50% and 100% of the maximum force.20 Root mean square (RMS) EMG amplitudes of the medial gastrocnemius muscle, corresponding to the plateau level of plantarflexion MVIC, were recorded and quantified for 1.0 second epochs for side-to-side comparisons.

The measurements of fascicle behaviors, muscle-tendon length, and kinematic data during heel raising and lowering were taken via a B-mode ultrasonography and synchronized using a full HD and infrared camera-integrated video analysis system (138-2, Noraxon, Scottsdale, AZ). Reflective markers were placed and fixed on the upper part of the posterior calcaneal tuberosity, lateral aspect of the fifth metatarsal head, lateral malleolus, fibular head, femoral epicondyle, and thigh at 50% of the distance between the greater trochanter of the femur and the lateral tibiofemoral joint line of the tested leg of each participant.6 The positions of the markers representing the thigh (femoral epicondyle and 50% thigh), lower leg (lateral malleolus and fibular head), and foot (lateral malleolus and fifth metatarsal head) were used to calculate the sagittal plane knee and ankle joint angles. The participants stood on the step (35 cm height, 40 cm width, and 40 cm length) with equal weightbearing on both feet. The spatial location of the Achilles tendon at the insertion on the calcaneal tuberosity (I) and the myotendinous junction (J) and head (H) of the medial gastrocnemius muscle were identified by output ultrasound images and the 2-D video space. The position and orientation of the transducer were tracked by the video analysis system and 2 reflective markers (diameter = 19 mm) positioned on one side of the plastic housing of the transducer. The distances between these locations were defined as the standing muscle length (LMG; J to H) and standing Achilles tendon length (LAT; I to J) (Table 1). The transducer was secured by a custommade holder to fix the transducer perpendicular to the belly of the medial gastrocnemius muscle and minimize any transducer movement relative to the muscle or ankle movements (Figure 1A). Each participant's single tested leg stood with the forefoot positioned in the middle of the edge of the step to allow full dorsiflexion to be reached. The step was placed beside a wall, allowing each participant to touch the wall with an index finger at the shoulder level to maintain a steady 1-leg standing position.34 The given participant was then instructed to perform 2 sets of exercise tasks, with each set consisting of 3 cycles of full weightbearing ankle concentric (raising heel to the peak ankle plantarflexion angle) and eccentric (lowering to the peak ankle dorsiflexion angle) exercises in a controlled manner. The concentric and eccentric phases were identified from the sagittal ankle joint angles by the video analysis system (Figure 1B). The measurement restarted if the given participant could not keep pace with the metronome, keep his or her trunk straight, or if he or she lost his or her balance. The pace of the ankle movements was guided by a metronome set at 60 beats per minute giving 4 beats for a full cycle of plantarflexion and dorsiflexion. The length of the muscle-tendon unit of the medial gastrocnemius (LMTU) during the exercise tasks was defined as the summation of the standing length of the muscle and tendon (ie, LMG + LAT) and the change of the length (△LMTU), which was calculated using the following formula10:

$\Delta L_{MTU}=C_0+C_1(\theta_H)+C_2(\theta_K)+C_3(\theta_K)^2+C_4(\theta_A)$,

Where θ_K is the knee angle, θ_A is the ankle angle, $C_0=0.9$, $C_1=0$, $C_2=-0.00062$, $C_3=0$, and $C_4=0.00214$

The length of the tendinous tissue (LTT) during the exercise tasks was subtracted from the length of the muscle-tendon unit of the medial gastrocnemius (LMTU) after accounting for the fascicular architecture with the following formula8:

$L_{TT}=L_{MTU}-(L_f\times\cos\theta)$,

where L and θ are the fascicle length and pennation angle of the fascicle, respectively. The averaged ultrasonographic data and the lengths were gathered during the second and third consecutive cycles in 2 exercise sets at different times normalized to a relative percentage of the duration of the concentric and eccentric phases (linear length normalization) in jumps of 5% from 0% to 100%. The vertical distance between the highest and lowest heel heights during the concentric and eccentric phases, respectively, was defined as the maximal heel-raise-lower distance.

This 2-set heel exercise was repeated again with wireless surface EMG recording electrodes, without the transducer, to record the myoelectrical activities of the medial gastrocnemius and tibialis anterior muscles. Amplitudes (mV) of RMS EMG of the gastrocnemius muscle were quantified corresponding to the concentric and eccentric phases in the second and third full movement cycles. The change of the fascicle angle, change of the fascicle length, and length changes of the tendinous tissue between the values at peak plantarflexion and peak dorsiflexion were recorded for subsequent correlation tests.

After the measurements, each participant indicated the clinical severity of their Achilles tendon pain by filling out the Victorian Institute of Sports Assessment–Achilles (VISA-A) questionnaire.33

Statistical Analyses

Based on our pilot works and on the basis of a value of .05 for alpha (α) and a power of .80 for the statistical test, the sample size required for significant differences between the repaired and noninjured legs was 12 for the aponeurosis stiffness. It was therefore decided to recruit more than 15 participants for this study. The Wilcoxon signed rank test was used to analyze the differences between the repaired legs and noninjured legs in terms of the values of the fascicle morphologies, muscle-tendon length, mechanical properties of the muscle aponeurosis, EMG, and maximal heel-raise-lower distance (Tables 1 and 2). The Spearman's rank correlation coefficient was calculated to determine whether the change magnitude of the fascicle or tendinous tissue length, from the beginning to the end of the phase, in the medial gastrocnemius muscle or the stiffness of the muscle's proximal aponeurosis would correlate with the maximal heel-raise-lower distance. The Cronbach's alpha coefficient was calculated to measure the internal consistency of the change magnitude. The data were analyzed using software (SPSS Inc, Chicago, IL) with the alpha level set at .05.

Results

Twenty participants with a unilateral Achilles tendon repair and 8 healthy participants were recruited, and their characteristics are shown in Table 3. No patients required exclusion. The fascicle length prior to the isometric contraction, mechanical stiffness of the aponeurosis during the isometric contraction, standing lengths of the medial gastrocnemius muscle and Achilles tendon, length of the muscle-tendon unit and tendinous tissue, and maximal single-legged heel-raise heights during the dynamic exercise are summarized in Table 1 and showed significant differences between the repaired and noninjured legs (Ps ranged between .049 and .003). During the concentric and eccentric phases of the exercise, there were significant differences in the fascicle length (Ps ranged between .028 and <.001), fascicle angles (Ps ranged between .044 and .007), and tendinous tissue length (Ps ranged between .03 and <.001) (Figure 2). Significant results were found in the fascicle, tendinous tissue, and fascicle angle during the concentric and eccentric phases (Figure 2A), except for during the late phase of the concentric and early phase of the eccentric contractions (Figures 2B and 2C). There was no similar significance for the length of the muscle-tendon unit (Figure 2D). There were side-to-side differences in the morphomechanical change magnitudes and also correlations between the change magnitudes and the MVIC or heel-raise-lower distance, including in the change magnitudes for fascicle length (rs ranged between .511 and .760, Ps ranged between .001 and <.001), tendinous tissue length (rs ranged between .511 and .751, Ps ranged between .001 and <.001), and the stiffness of the proximal aponeurosis ($r = .577$, $P < .001$) (Table 2). The Cronbach's alpha coefficients in the measurements of change magnitudes regarding fascicle length and length ranged between .929 and .733 (Table 2).

Discussion

This study examined the side-to-side differences in the morphomechanical characteristics of the myotendinous complex prior to or during isometric, concentric, and eccentric phases of the exercises during the 3- to 12-month timeframe after an Achilles rupture. We evaluated the fascicle length, myotendinous length, and aponeurosis stiffness in the gastrocnemius muscle in addition to the significant difference in the MVIC torques and heel raise distance. The comparisons also include the differences in the change magnitudes of lengths of the fascicle and tendinous tissue, which together with aponeurosis stiffness were correlated with the outcomes of the exercise related to force production in ankle plantarflexion. These findings confirmed the hypothesis that morphomechanical characteristics in the gastrocnemius muscle affect rehabilitation outcomes in regards to force production. These characteristics attenuate the relative contributions of the muscle components to the ankle performance during a clinically validated test. This study has suggested that optimal muscle function after an Achilles rupture is probably achieved by maintaining or increasing muscle length, elastic stiffness, and mass. However, additional studies are needed to investigate the prognostic ability of these findings in practice.

Our comparisons between the repaired and noninjured leg groups prior to the tests showed that there were shorter resting fascicle and standing muscle lengths as well as longer standing lengths of the Achilles tendon and lower aponeurosis stiffness in the repaired legs. Our results are comparable with those of previous studies regarding Achilles tendon lengthening and fascicle shortening after an Achilles rupture.11,15,36,38 The shortening of the muscle fascicle after the rupture may be caused by lengthening of the Achilles tendon or alterations in sarcomere structure, for example, reductions in their length or number.11,15 The shortened fascicle accompanied by a longer tendon length and reduced aponeurosis stiffness may lead in turn to (1) a reduced relative fascicle shortening amplitude and velocity as well as a shift in the length-tension relationship of the muscle1 and (2) a reduced contribution to passive lengthening of the muscle-tendon unit and a faster rate of stretch applied directly to fascicles when the muscle is lengthened.14,17 The reduced relative fascicle shortening or lengthening is supported by the finding indicating a reduced change magnitude in fascicle length observed during the isometric test and dynamic exercise (Table 2). The shift in the length-tension relationship of the gastrocnemius muscle is supported by a previous study that demonstrated end-range strength defects.27 The results of the present study indicate that the restoration of morphological characteristics should be considered in the surgical procedure and early stage rehabilitation after an Achilles rupture to better ensure the full recovery of different types of muscle function.

Our findings substantially demonstrated side-to-side differences in fascicle geometry (length and angle) and tendon lengthening during the concentric and eccentric contractions during medium-term follow-up. The fascicle length was shortening and lengthening, respectively, as the foot was raising and lowering, whereas the fascicle angle and tendinous tissue demonstrated contrasting results (Figure 2). These results regarding fascicle tendon interaction are consistent with those reported by other authors in healthy subjects.20,31 The data presented in Figure 2C also support the view that the tendinous tissue length in the plantarflexion position is longer than it is in the dorsiflexion position (P values not being shown) and are consistent with the length previously reported in an isometric condition.9 Taken together, our results further demonstrate that when performing ankle plantarflexion, there was diminished force production potential because of alteration of the muscle fascicle force-length relationship9,19,23 as well as compromising of the transmission of force to the aponeurosis due to an increase in the pennation angle attenuating the extent of fascicle shortening in the legs with an Achilles rupture.1,15 These findings, combined with the results regarding low aponeurosis stiffness, indicate that there is less elastic potential energy that can be utilized or restored in the muscle over the full range of the plantar and dorsiflexion of heel raising and lowering when compared to noninjured legs.[8,35] In addition, it is suggested that an increase in the fascicle angle attenuates the extent of fascicle shortening.[16,32] In this study, with the numbers available, the insignificant side-to-side differences in the fascicle angles and tendinous tissue length when the participants approached the end range of the concentric contraction indicated that there was no significant alteration of the shortening velocity of the muscle modulated by the fascicle angle in the legs with an Achilles rupture[1] and that fascicle length may become the most crucial factor in determining the restrictions in the operation range and strength of muscle contraction or performance in the end range of plantarflexion. Therefore, selecting appropriate treatments aimed at minimizing the muscle length shortening is fundamental to the objectives of rehabilitation.

It would seem that nonoperative treatment of a rupture would not be able to restore the original muscle-tendon unit length and tension of the gastrocnemius muscles. Surgical treatment has been shown to provide an earlier return to work and slightly stronger plantarflexion strength.[37] The treatments applied to an Achilles tendon rupture may include a standardized surgical procedure to achieve proper tendon tension and the integration of an inner range eccentric exercise to restore normal muscle length early after the surgical repair.[22] To establish proper tendon tension, it is suggested that patients be operated on in a prone position under local anesthesia so that they can actively perform plantarflexion pre- and posttightening of the tendon. This procedure, which has been routinely used by one of the coauthors (C.R.), in which the foot hangs over the edge of the operating table, also allows Thompson's test to be executed intraoperatively and thus allows the tightening of the Achilles tendon repair in a position as close to the neutral position as possible. Furthermore, eccentric contractions in the shortest position of the triceps surae muscles, namely, in a plantarflexion position (inner range exercise), are advisable to reestablish proper sarcomere length and sarcomere number and increase the mechanical properties of the myotendinous complex.[7,11,22,26] It is suggested that this eccentric exercise be initiated at 5 weeks postoperation to restore normal muscle length.[11] Although previous studies have also advocated for the use of this surgical procedure and inner range eccentric exercise, few studies have combined the procedure and exercise and observed the subsequent outcomes. As such, future studies are encouraged to investigate the therapeutic effects of the combination and compare those effects with those of other common treatment protocols for an Achilles rupture.

The side-to-side comparisons also included a comparison of the plantarflexion MVIC torque, heel-raise-lower distance (Table 1), and magnitude of the morphological changes in terms of fascicle and tendinous tissue length (Table 2). The findings regarding these phenomena were consistent with those reported previously by studies investigating strength or functional deficits years after an Achilles rupture.4,5,28,30 The side-to-side comparisons regarding the magnitude of the morphological changes and correlations between the changes and outcomes involving force production (Table 2) again indicated that the combined effects of muscle morphomechanical alterations after a rupture limit the operation range of the muscle fascicle and are unfavorable for force production at the ankle joint.15 Although the methodology and correlation analyses utilized in this study to determine the relationship between functional performances and the magnitude of morphological changes may not be practical for clinical use, the results of the analyses may be helpful for understanding the mechanisms behind a good or poor treatment outcome after an Achilles rupture or how a change in the (Frank-Starling) length-tension relationship affects the force-generating range of the muscle in a stretch-shortening contraction. Our results for the reliability group demonstrate that these change magnitudes of the fascicle geometry (angle and length) are reliable and should be utilized in future follow-up studies in terms of recording the change magnitudes over the time course of tendon healing. With the participant numbers available, the results regarding the insignificant change magnitudes in the fascicle angle and the RMS EMG indicate the use of compensatory strategies in the repaired legs and imply that morphological measurements may be superior to EMG evaluations after a rupture.

The limitations of this study include its retrospective study design, small sample size, wide range of participant ages, and diversity of inclusion criteria, as well as the 3- to 12-month period of subject recruitment, which together made it impossible for this study to differentiate the morphomechanical characteristics in patients during or after the postoperative rehabilitation process. The current study utilized a side-to-side comparison to measure adaptation in morphomechanical properties following an Achilles rupture. Therefore, care must be taken in interpreting results when using the noninjured leg as the reference because the adaptations in the noninjured legs may also be postoperative time and recovery dependent. As such, the differences in the measurement results in the repaired and noninjured legs may have been artificially decreased. Furthermore, changes in dynamic muscle morphology appear to depend on the contraction speed involved2; therefore, our results may be not applicable to other exercises involving different preloading or speed of movements.

Conclusions

The findings of this study substantiate the conclusion that the combined effects of the dynamic morphomechanical changes in the calf muscle after an Achilles tendon rupture are related to functional deficits. Selecting the appropriate surgical repair and rehabilitation for Achilles tendon ruptures is recommended for restoring the length and mechanical strength of the muscle-tendon unit of plantar-flexion muscles.

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Declaration of Conflicting Interests

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References

1. Azizi E, Brainerd EL, Roberts TJ. Variable gearing in pennate muscles. Proc Natl Acad Sci U S A. 2008;105:1745-1750.

2. Barber LA, Barrett RS, Gillett JG, Cresswell AG, Lichtwark GA. Neuromechanical properties of the triceps surae in young and older adults. Exp Gerontol. 2013;48:1147-1155.

3. Bostick GP, Jomha NM, Suchak AA, Beaupré LA. Factors associated with calf muscle endurance recovery 1 year after achilles tendon rupture repair. J Orthop Sports Phys Ther.

2010;40:345-351.

4. Brorsson A, Grävare Silbernagel K, Olsson N, Nilsson Helander K. Calf muscle performance deficits remain 7 years after an Achilles tendon rupture. Am J Sports Med. 2018;46(2):470-477.

5. Brorsson A, Willy RW, Tranberg R, Grävare Silbernagel K. Heel-rise height deficit 1 year after Achilles tendon rupture relates to changes in ankle biomechanics 6 years after injury. Am J Sports Med. 2017;45(13):3060-3068.

6. Chaudhry S, Morrissey D, Woledge RC, Bader DL, Screen HR. Eccentric and concentric loading of the triceps surae: an in vivo study of dynamic muscle and tendon biomechanical parameters. J Appl Biomech. 2015;31:69-78.

7. Duclay J, Martin A, Duclay A, Cometti G, Pousson M. Behavior of fascicles and the myotendinous junction of human medial gastrocnemius following eccentric strength training. Muscle Nerve. 2009;39:819-827.

8. Fukunaga T, Ichinose Y, Ito M, Kawakami Y, Fukashiro S. Determination of fascicle length and pennation in a contracting human muscle in vivo. J Appl Physiol. 1997;82(1): 354-358.

9. Fukutani A, Misaki J, Isaka T. Relationship between joint torque and muscle fascicle shortening at various joint angles and intensities in the plantar flexors. Sci Rep. 2017;7:290.

10. Hawkins D, Hull ML. A method for determining lower extremity muscle-tendon lengths during flexion/extension movements. J Biomech. 1990;23:487-494.

11. Heikkinen J, Lantto I, Piilonen J, et al. Tendon length, calf muscle atrophy, and strength deficit after acute Achilles tendon rupture: long-term follow-up of patients in a previous study. J Bone Joint Surg Am. 2017;99:1509-1515.

12. Hoffman BW, Cresswell AG, Carroll TJ, Lichtwark GA. Muscle fascicle strains in human gastrocnemius during backward downhill walking. J Appl Physiol. 2014;116:1455-1462.

13. Hopkins PM. Skeletal muscle physiology. CEACCP. 2006;6(1):1-6.

14. Ishikawa M, Niemelä E, Komi PV. Interaction between fascicle and tendinous tissues in short-contact stretch-shortening cycle exercise with varying eccentric intensities. J Appl Physiol. 2005;99:217-223.

15. Jamali AA, Afshar P, Abrams RA, Lieber RL. Skeletal muscle response to tenotomy. Muscle Nerve. 2000;23:851-862.

16. Kangas J, Pajala A, Ohtonen P, Leppilahti J. Achilles tendon elongation after rupture repair: a randomized comparison of 2 postoperative regimens. Am J Sports Med. 2007;35:59-64.

17. Kawakami Y, Ichinose Y, Fukunaga T. Architectural and functional features of human triceps surae muscles during contraction. J Appl Physiol. 1998;85:398-404.

18. Konow N, Azizi E, Roberts TJ. Muscle power attenuation by tendon during energy dissipation. Proc Biol Sci. 2012;279:1108-1113.

19. Kubo K, Kanehisa H, Azuma K, et al. Muscle architectural characteristics in young and elderly men and women. Int J Sports Med. 2003;24:125-130.

20. Kubo K, Kanehisa H, Kawakami Y, Fukunaga T. Influence of static stretching on viscoelastic properties of human tendon structures in vivo. J Appl Physiol. 2001;90:520-527.

21. Kubo K, Kanehisa H, Takeshita D, Kawakami Y, Fukashiro S, Fukunaga T. In vivo dynamics of human medial gastrocnemius muscle-tendon complex during stretch-shortening cycle exercise. Acta Physiol Scand. 2000;170:127-135.

22. Leppilahti J, Lähde S, Forsman K, Kangas J, Kauranen K, Orava S. Relationship between calf muscle size and strength after achilles rupture repair. Foot Ankle Int. 2000;21(4):330-335.

23. Lichtwark GA, Wilson AM. Interactions between the human gastrocnemius muscle and the Achilles tendon during incline, level and decline locomotion. J Exp Biol. 2006;209: 4379-4388.

24. Maffulli N, Kenward MG, Testa V, Capasso G, Regine R, King J. Clinical diagnosis of Achilles tendinopathy with tendinosis. Clin J Sport Med. 2003;13:11-15.

25. Magnusson SP, Aagaard P, Dyhre-Poulsen P, Kjaer M. Loaddisplacement properties of the human triceps surae aponeurosis in vivo. J Physiol. 2001;531: 277-288.

26. Maquirriain J. Achilles tendon rupture: avoiding tendon lengthening during surgical repair and rehabilitation. Yale J Biol Med. 2011;84(3):289-300.

27. Mullaney MJ, McHugh MP, Tyler TF, Nicholas SJ, Lee SJ. Weakness in end-range plantar flexion after Achilles tendon repair. Am J Sports Med. 2006;34(7):1120-1125.

28. Olsson N, Nilsson-Helander K, Karlsson J, et al. Major functional deficits persist 2 years after acute Achilles tendon rupture. Knee Surg Sports Traumatol Arthrosc. 2011;19(8):1385-1393.

29. O'Reilly MA, Massouh H. Pictorial review: the sonographic diagnosis of pathology in the Achilles tendon. Clin Radiol. 1993;48:202-206.

30. Peng WC, Chang YP, Chao YH, et al. Morphomechanical alterations in the medial gastrocnemius muscle in patients with a repaired Achilles tendon: associations with outcome measures. Clin Biomech. 2017;43:50-57.

31. Reeves ND, Narici MV. Behavior of human muscle fascicles during shortening and lengthening contractions in vivo. J Appl Physiol. 2003;95(3):1090-1096.

32. Roberts TJ, Azizi E. The series-elastic shock absorber: tendons attenuate muscle power during eccentric actions. J Appl Physiol. 2010;109:396-404.

33. Robinson JM, Cook JL, Purdam C, et al. The VISA-A questionnaire: a valid and reliable index of the clinical severity of Achilles tendinopathy. Br J Sports Med. 2001;35:335-341.

34. Schepull T, Kvist J, Andersson C, Aspenberg P. Mechanical properties during healing of Achilles tendon ruptures to predict final outcome: a pilot Roentgen stereophotogrammetric analysis in 10 patients. BMC Musculoskelet Disord. 2007;8:116.

35. Silbernagel KG, Nilsson-Helander K, Thomeé R, Eriksson BI, Karlsson J. A new measurement of heel-rise endurance with the ability to detect functional deficits in patients with Achilles tendon rupture. Knee Surg Sports Traumatol Arthrosc. 2010;18(2):258-264.

36. Silbernagel KG, Steele R, Manal K. Deficits in heel-rise height and achilles tendon elongation occur in patients recovering from an Achilles tendon rupture. Am J Sports Med. 2012;40:1564-1571.

37. Soroceanu A, Sidhwa F, Aarabi S, Kaufman A, Glazebrook M. Surgical versus nonsurgical treatment of acute Achilles tendon rupture: a meta-analysis of randomized trials. J Bone Joint Surg Am. 2012;94(23):2136-2143.

38. Strom AC, Casillas MM. Achilles tendon rehabilitation. Foot Ankle Clin. 2009;14:773-782.

39. Suydam SM, Buchanan TS, Manal K, Silbernagel KG. Compensatory muscle activation caused by tendon lengthening post-Achilles tendon rupture. Knee Surg Sports Traumatol Arthrosc. 2015;23:868-874.

40. Wang HK, Chiang H, Chen WS, Shih TT, Huang YC, Jiang CC. Early neuromechanical outcomes of the triceps surae muscle-tendon after an Achilles’ tendon repair. Arch Phys Med Rehabil. 2013;94:1590-1598.

Table 1. Main Results of Morphomechanical Measurements and Outcome Measurements in the Repaired and Nonrepaired Leg Isometric Tests and Dynamic Exercise.

	Repaired Legs	Nonrepaired Legs	*P* Value
Resting prior to isometric test			
Fascicle angle (degree)	21.7 (13.8-35.2)	22.3 (13.0-32.9)	.550
Fascicle length (mm)	46.7 (23.3-71.7)	56.5 (37.9-85.5)	.014
Isometric test			
Maximal torque (Nm)	88.5 (30.5-144.6)	133.2 (47.0-183.5)	<.001
Aponeurosis stiffness (N/mm)	374.0 (88.3-723.7)	562.1 (166.1-1485.2)	.003
RMS EMG MG (mV)	256.3 (126.7-535.7)	325.8 (158.7-652.2)	.351
Prior to dynamic test			
Standing muscle length (mm)	221.3 (154.4-264.2)	230.0 (183.8-278.1)	.049
Standing tendon length (mm)	174.2 (129.5-214.1)	160.2 (133.1-236.5)	.044
Dynamic test			
CON RMS EMG MG (mV)	266.2 (145.3-563.1)	302.9 (146.4-514.9)	.179
ECC RMS EMG MG (mV)	182.2 (100.8-343.5)	198.8 (97.2-435.4)	.737
CON Heel-raise-lower distance (mm)	47.9 (20.2-95.6)	83.2 (50.5-114.8)	<.001
ECC Heel-raise-lower distance (mm)	48.5 (19.7-89.6)	79.9 (50.1-116.1)	<.001

Abbreviations: CON, concentric; ECC, eccentric; EMG, electromyography; MG, medial gastrocnemius; RMS, root mean square.
[a]Results are presented as median values, with the range between the minimum and maximum in the parentheses.

Table 2. Correlations Between Change Magnitudes of the Morphology With Performance.

Table 2. Correlations Between Change Magnitudes of the Morphology With Performance.

Tests	Cronbach's α	Side-to-Side Difference *P* Value	Variable
Isometric			Plantarflexion MVIC torque
ΔFascicle length[a]	.865	<.001	r = .511, *P* = .001
ΔFascicle angle[b]	.733	.191	r = .336, *P* = .034
ΔTendinous tissue length[c]	.189	<.001	r = .511, *P* = .001
Aponeurosis stiffness		.003	r = .577, *P* < .001
Concentric			Heel-raise-lower distance
ΔFascicle length[d]	.929	.001	r = .760, *P* < .001
ΔFascicle angle[e]	.738	.478	r = .291, *P* = .069
ΔTendinous tissue[f]	.120	.001	r = .751, *P* < .001
Eccentric			Heel-raise-lower distance
ΔFascicle length[g]	.917	.001	r = .739, *P* < .001
ΔFascicle angle[h]	.733	.881	r = .194, *P* = .229
ΔTendinous tissue[i]	.110	.001	r = .734, *P* < .001

Abbreviations: Δ, changes found between rest and MVIC or changes between initiation and end of the concentric or eccentric phase; MVIC, maximal voluntary isometric contraction.

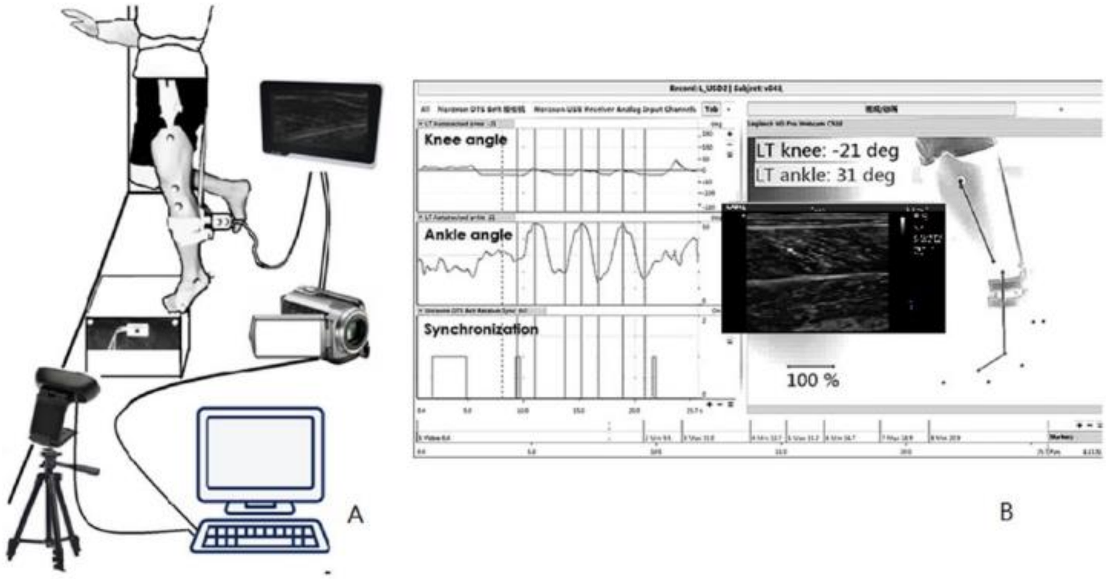

Figure 1 Experimental setting and example of offline analyses of joint angle and muscle fascicle of the medial gastrocnemius muscle recorded from the initiation of a set of heel-raising and -lowering exercise for 1 subject. (A) Represents the experimental setting and (B) the 3 repetitions of the exercise. LT, Left. Vertical lines indicate synchronization signal of onset and end of the exercise and also demarcate the concentric and eccentric phases of the exercise.

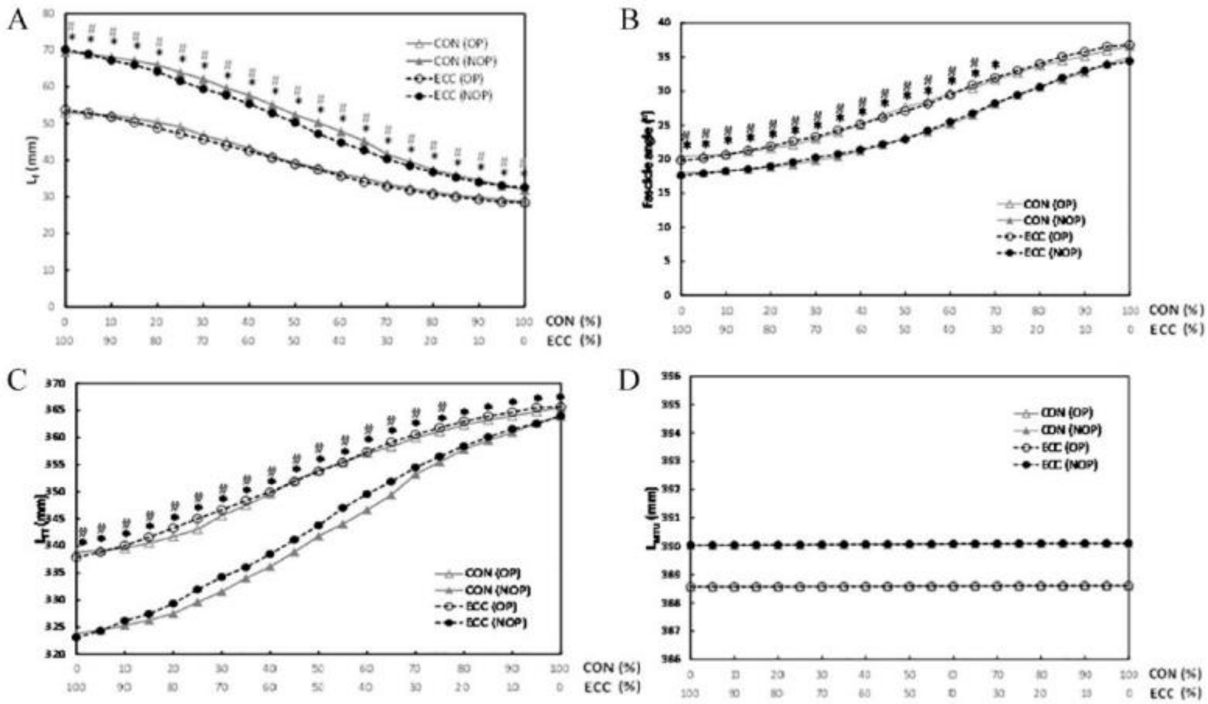

Figure 2 Records and comparisons of the measured parameters, (A) fascicle length, (B) fascicle angle, (C) tendinous tissue length, and (D) musculotendinous complex length, at different times normalized to a relative percentage of the duration of the concentric and eccentric phases, from 0% to 100%, in intervals of 5%. Values are means ± SE. The differences in the concentric and eccentric phases are marked with # and *, respectively. The P values in (A) ranged between .028 and <.001 for # and between .012 and <.001 for *, the P values in (B) ranged between .044 and .019 for # and between .04 and .007 for *, and the P values in (C) ranged between .027 and <.001 for # and between .03 and <.001 for *.