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Title

Morphomechanical alterations in the medial gastrocnemius muscle in patients with a repaired Achilles tendon: Associations with outcome measures

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Highlights

•Morphological changes and mechanical properties in the calf muscle were measured.

•There are muscular adaptations of a leg within 6 months of an Achilles tendon repair.

•The morphomechanical features correlate with performances in the lower extremities.

•The morphomechanical alterations should be monitored during functional restoration.

Abstract

Background

Functional deficits are found in ankles that have sustained an Achilles rupture. This study sought to evaluate and compare the morphomechanical characteristics of the medial gastrocnemius muscle in the legs of participants within six months of a unilateral Achilles repair to determine any correlations between those characteristics and objective outcomes and self-reported functional levels.

Methods

Fifteen participants were assessed via measurements of muscle morphologies (fascicle length, pennation angle, and muscle thickness) in a resting state, the mechanical properties of the proximal aponeurosis of the medial gastrocnemius muscle, the pennation angle during ramping maximal voluntary isometric contractions (MVIC), the heel raise test, and the Taiwan Chinese version of the Lower Extremity Functional Scale (LEFS-TC) questionnaire.

Findings

Compared with the non-injured legs, the repaired legs showed a lower muscle fascicle length (mean 4.4 vs. 5.0 cm) and thickness (1.7 vs. 1.9 cm), lower stiffness of the GM tendon and aponeurosis (174.1 vs. 375.6 N/mm), and a greater GM pennation angle (31.2 vs. 28.9°) during 90% MVIC (all $p \leq 0.05$). Correlations were found between the morphomechanical results and maximal heel raise heights or the LEFS-TC score, and between the symmetry ratios of the fascicle lengths and the LEFS-TC score.

Interpretation

There are decreases in fascicle length, muscle thickness and mechanical properties in the medial gastrocnemius muscles of the participants within the first six months after an Achilles repair. These morphomechanical alterations demonstrate associations with functional levels in the lower extremities and indicated the need for early mobilization of the calf muscles after the repair.

Keywords

Muscle morphology; Aponeurosis; Viscoelasticity; Tendinous tissue; Achilles rupture

1. Introduction

Incidences of acute Achilles tendon ruptures have increased in the past several decades and have recently ranged from 21.5 to 47.0 (per 100,000 person-years) in populations participating in sports (Huttunen et al., 2014, Lantto et al., 2015). Rehabilitation programs after an Achilles rupture commonly initiate from ankle immobilization in either conservative or surgical managements (Holm et al., 2015). In one study, functional reductions in the ankle plantarflexion torque, heel-raise height, and range of dorsiflexion were observed in subjects 10 years after an Achilles rupture, implying long-term morphomechanical impacts following tendon rupture and subsequent immobilization (Horstmann et al., 2012). Relatedly, one study on rodents has demonstrated morphological changes, including decreases of soleus muscle fascicle length and pennation angle subsequent to weeks of ankle immobilization in a plantarflexion position (Williams and Goldspink, 1978). These changes to geometric aspects of the arrangement of the fascicles may lead to lower force outputs and reductions in the shortening length of the muscle when going through the full anatomical range of joint motion, i.e., muscle excursion (Narici and Maganaris, 2006, Rassier et al., 1999). Since gastrocnemius muscle atrophy was observed in patients with an Achilles rupture (Suydam et al., 2015), it is rational to anticipate that the observed morphological changes are associated with functional impairment of the legs when engaged in actions involving force transmission and muscle exertion, such as the heel raise (Ishikawa et al., 2007, Lichtwark and Wilson, 2008). However, few human studies have provided evidence to support this hypothesis.

Previous studies recruiting participants within one year of an Achilles repair have shown decreases in tendon stiffness and energy storage during passive ankle dorsiflexion in the injured Achilles tendon (McNair et al., 2013, Schepull et al., 2012, Wang et al., 2013). It was also found that the elasticity modulus of the Achilles tendon post-rupture was correlated with the heel-raise index after tendon injury (Schepull et al., 2012). In vivo analysis of the triceps surae muscle-tendon unit conducted 2 years after the Achilles tendon reconstruction have variously shown that there are (1) reductions in stress at maximal voluntary force, in Young's modulus and in stiffness in the repaired leg, whether in an early mobilization group or an immobilization group (Geremia et al., 2015); and (2) increases of unilateral tendon stiffness 2–6 years after the tendon rupture (Agres et al., 2015). Theoretically, the primary joint effects of tendon elasticity and pennation angle include reducing the fibre length variations in isometric contractions (Legreneur et al., 1997). These altered tendon mechanical properties after the Achilles rupture should be accompanied with changes of the pennation angles during and at different force levels of isometric contractions. In addition, the aforementioned changes may affect the mechanical efficiency of muscle force (Kawakami et al., 1998). However, the fascicle behaviors at different force levels and the associations between the aforementioned morphomechanical alterations in the calf muscle and heel raise height have still not been definitively determined. In addition, studies focused on the mechanical properties of the aponeurosis where the contractile fascicle is attached should also show a correlation to heel-raise capacity. In this study, we sought to evaluate the morphological characteristics of the medial gastrocnemius muscle in a relaxed condition and during contractions, the mechanical properties of the aponeurosis and heel raise height, and the self-reported lower extremity functional levels of participants within the first six months after a unilateral Achilles repair. We hypothesized that, when compared to the contralateral non-injured legs of these participants, the repaired legs would exhibit significantly decreased fascicle lengths and pennation angle in a relaxed muscle condition, decreased mechanical properties in the proximal aponeurosis of the medial gastrocnemius muscle, or greater pennation angles during isometric contractions. In addition, we hypothesized that the mechanical properties of the muscle's proximal aponeurosis or the muscle morphology outcomes of the medial gastrocnemius muscle would correlate with the heel raise height, and that the morphomechanical symmetries of the muscle would be associated with the participants' self-reported functional levels.

2. Methods

2.1. Subjects and study design

The study was approved by the institutional review boards of National Taiwan University Hospital (reference no. 201303086RINC), Taipei Veterans General Hospital (reference no. 2013-08-031B) and Shin Kong Wu Ho-Su Memorial Hospital (reference no. 20130602R) and was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. Written informed consent was obtained from all participants prior to participation and details that might disclose the identity of the subjects under our study have been omitted. Four surgical groups that primarily use the Kessler suturing technique to repair ruptured Achilles tendons and that recommend a 16-week rehabilitation protocol (Table 1, adapted from Strom and Casillas, 2009) after such repairs were invited to join the study for subject recruitment. Inclusion criteria required the participants to be aged between 20 and 60 years old and to have suffered from a unilateral Achilles tendon rupture followed by surgical management within the past three to six months. Participants were excluded if they: (1) exhibited any positive signs or evidence of tendinopathy in their non-injured control leg as determined by physical examination (Maffulli et al., 2003) or ultrasonographic screening (O'Reilly and Massouh, 1993) with a 5–12 MHz broadband linear array transducer (EnVisor, Philips Medical Systems, Inc., Bothell, USA); (2) had a delayed surgery (> 1 week) or were diagnosed with a sural nerve injury; (3) did not complete the 16-week protocol with physiotherapists. All measurements were taken for both legs in the order of a block randomization scheme. There was a 10-min interval of rest between the measurements for the two legs.

2.2. Muscle morphology and aponeurosis mechanical properties

Each subject lay prone (face down) on an examination bed with both ankles hanging over the edge of the bed using the techniques described in previous studies (Wang et al., 2013). The foot was positioned at a 90° angle relative to the tibia and fixed on a footplate. A load cell (model S6001; Celtron Techniques Inc., Taipei, Taiwan) connected to the footplate was used to record voluntary or evoked isometric plantar/dorsiflexion torque (Nm) (Fig. 1A). Ankle fixation was assessed by continuous recording of the degree of ankle flexion by an electrogoniometer (Sharp Sensor S700, Measurand Inc., Fredericton, Canada), connected to an MP100 system (BIOPAC Systems Inc., Santa Barbara, USA) (same for the load cell). Myoelectrical activities of the tibialis anterior were measured using one pair of TSD150B (Biopac Systems Inc., USA) active-surface EMG-recording electrodes (stainless steel disk diameter 11.4 mm, disk spacing 20 mm, impedance = 100 MΩ; gain = 350). The electrodes were positioned parallel to the tibia at approximately one-third the distance between the knee and ankle. The reference electrode was placed on the lateral malleolus of the ankle (Wang et al., 2013). The skin was prepared prior to application of the surface electrodes, and a portable EMG unit (Sierra II; Cadwell, Kennewick, US) was used to ensure that the inter-electrode resistance was below 5 kΩ. Signals from the surface electrodes were sampled at 1000 Hz with a common mode rejection ratio of 95 dB, amplified, and band pass filtered from 12 to 500 Hz. These active recording electrodes were connected to an interface (HLT-100C) of the MP100 system, and the MP100 system was connected to a computer (D672; ASUS, Taipei, Taiwan, ROC) using AcqKnowledge 3.8 acquisition software (Biopac Systems Inc., USA). The participants were instructed to relax for 10 min. Muscle morphologies in a relaxed muscle condition, including fascicle length, pennation angle, and muscle thickness, were taken by ultrasonograph according to definitions provided in a previous study (Kubo et al., 2003) at a site corresponding to the proximal third (i.e., the distance between the lateral malleolus of the ankle and the lateral condyle of the knee) of the gastrocnemius medialis muscle. Muscle thickness was measured as the distance between the superficial and deep aponeuroses at the mid-line of the image. 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 muscles (Fig. 1B and C). The fascicle length was calculated by dividing the thickness by the sine component of the pennation angle (Kubo et al., 2003). The ultrasound probe was therefore firstly placed on the medial gastrocnemius muscle belly while measuring muscle morphologies in a relaxed muscle condition, and then applied on the myotendinous junction for the morphomechanical measurements (pennation angle and aponeurosis stiffness) during maximal voluntary isometric contractions (MVIC). Our previous work with 7 healthy individuals indicated that the intraclass correlation coefficients (ICCs) were 0.94 and 0.91, respectively, for the fascicle angle and fascicle length when the muscle was at rest.

The mechanical properties of the aponeurosis and the muscle morphologies during dynamic contraction, including the pennation angles in a muscle resting state and at 30%, 60%, and 90%

MVIC, were measured during ramping isometric contractions. To record the displacement, i.e., elongation, of the proximal aponeurosis between the gastrocnemius and the soleus muscle, as well as the pennation angle, the probe was placed in the sagittal plane over the distal part of the muscle where the myotendinous junction (i.e., the cross-point of the ultrasound echoes from the superficial and proximal aponeurosis) and a most identifiable cross-point from the fascicle and the proximal aponeurosis were respectively chosen as the initial locations for the measurement (Fig. 2). Each subject was then instructed to gradually increase plantarflexion force in their foot by starting from their forefoot and increasing from a relaxed status to MVIC within 5 s, after which the subject was asked to maintain MVIC for 1 s and then proceed from gradual to complete relaxation within 5 s. Elongation measurements of the proximal aponeurosis were taken during the ramping contraction by 5- to 10-MHz B-mode ultrasonography (Sonosite 180plus, SonoSite Inc., Seattle, USA) using the techniques described in previous studies (Magnusson et al., 2001, Wang et al., 2013). For synchronization, software containing simulating switching circuits written using LabVIEW 7.1 (National Instruments, Austin, USA) was used to add audio-electrical signals to the camera and MP100 system at the beginning and end of each measurement. Displacement digitalization of the junction was performed by the same examiner by using MATLAB 7.1 software (MathWorks, Massachusetts, USA). To ensure that the displacements of the myotendinous junction and the proximal aponeurosis of the gastrocnemius obtained during the isometric contractions were not overestimated by additional displacement from ankle plantarflexion, the additional displacements caused by manual passive ankle plantarflexion from 90° to 80° at a speed of approximately 5° per second were continuously recorded by the synchronized ultrasonography and electrogoniometer after the stiffness measurements were completed and the fixation between the load cell and foot plate was removed.

The measured plantarflexion torques (TQ) were converted to tendon force (Ft) by the following equation: Ft = TQ/MA, where the moment arm (MA) was determined from the lower leg length of each subject using the methodology of Kubo et al. (2002). The negative forces of the tibialis anterior during plantarflexion were estimated by the co-contraction EMG activities and the relationship between the dorsiflexion force and the root mean square EMG. 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 (Wang et al., 2013). Stiffness in the aponeurosis was defined as a slope of the ascending phase of muscle contraction between 50% and 100% of the maximum force (Kubo et al., 2001). The pennation angles in a resting state and at 30%, 60%, and 90% MIVC during force exertion were measured and recorded.

Afterwards, each participant was asked to stand beside the wall and perform maximal single-leg heel raises with the tested leg. Specifically, the participant was instructed to perform each maximal heel lift while also being allowed to touch the wall with an index finger at the shoulder level to maintain a steady one-leg standing position (Schepull et al., 2012). Participants performed at least 3 maximal trials for each leg, with the longest distance of lifting the heel off the ground for each leg recorded for analysis. The maximal vertical distance between the heel bottom and the floor was measured by a measuring tape. After the measurements, each participant indicated the functional level of his or her lower extremities by filling out the LEFS-TC questionnaire. Possible scores for the LEFS-TC questionnaire range from 0 to 80, with higher scores indicating fewer difficulties with functional activities (Binkley et al., 1999, Hou et al., 2014).

2.3. Statistical analyses

Based on our pilot works and on a basis of a value of 0.05 for alpha (α) and a power of 0.80 for the statistical test, the sample sizes required for significant differences between repaired and non-injured legs were 6, 10, 12 and 1133 for the aponeurosis stiffness, muscle thickness, fascicle length and pennation angle, respectively. It was therefore decided to recruit no < 12 subjects for this study. The Wilcoxon signed rank test was used to analyze the differences between the repaired legs and non-injured legs in terms of the values of the muscle morphologies and mechanical properties of the tendinous tissues. The Friedman test, a nonparametric one-way ANOVA, was used to compare the differences in the pennation angle between resting state, 30%, 60%, and 90% MVIC. The Spearman's rank correlation coefficient was calculated to determine (1) whether the muscle morphomechanical outcomes were correlated with heel raise height in each of the repaired and non-injured legs and pooled data for all the legs and (2) whether the symmetry ratios of the morphomechanical outcomes between the repaired and noninjured legs at rest were correlated with the LEFS-TC scores. This symmetry ratio was defined as a ratio of the repaired limb result and the non-injured limb result. The data were analyzed using SPSS 22.0 software (SPSS Inc., Chicago, USA) with the alpha level set at 0.05.

3. Results

Fifteen participants with a unilateral Achilles tendon rupture were recruited, and the participants' characteristics and LEFS-TC scores are shown in Table 2. None of the potential participants were excluded because of the exclusion criteria. The muscle morphologies at rest, the mechanical properties of the aponeurosis, and the maximal single-legged heel raise heights for the repaired and non-injured legs are summarized in Table 3. The maximal displacement of myotendinous junction and maximal calculated Achilles tendon force (in N) in the legs with an Achilles repair were significantly lower than those in the control non-injured legs (Table 3); however, differences of the maximal elongations of proximal aponeurosis in the medial gastrocnemius muscle between the repaired and non-injured legs were insignificant. The values of fascicle length and muscle thickness at the muscle belly in a relaxed muscle condition in the medial gastrocnemius muscle and the stiffness values of the tendinous tissues in the repaired legs were significantly lower than the corresponding values in the non-injured legs (Table 3) ($P < 0.05$). Spearman tests showed that the pennation angle and fascicle length in the repaired leg were correlated to the LEFS scores ($r = 0.58$, $p = 0.025$ and $r = -0.83$, $p < 0.001$ respectively). The results of the pennation angles in the proximal aponeurosis to myotendinous junction in a resting state and at 30%, 60%, and 90% MVIC in the repaired and non-injured legs are shown in Table 4. There were significant differences in the pennation angles at the four different levels of MVIC in both the repaired legs and the non-injured legs ($P < 0.001$). In addition, the pennation angle values at 90% MVIC in the repaired legs were significantly greater than the corresponding values in the non-injured legs (Table 4). There were correlations between the morphomechanical results (including fascicle length, muscle thickness, and the mechanical properties of the proximal aponeurosis) and the maximal heel raise heights, and between the symmetry ratios of the fascicle lengths and the LEFS-TC scores (the Spearman's rho values were 0.70, 0.53, 0.41, and − 0.92, respectively) (Fig. 3a–d).

4. Discussion

This cross-sectional study, which involved participants with a history of a unilateral Achilles tendon repair surgery within six months, confirmed our hypothesis that such participants would exhibit decreases of fascicle length, muscle thickness, and mechanical properties in the proximal aponeurosis of the medial gastrocnemius in their repaired legs. Furthermore, the morphomechanical characteristics of the participants, either in the repaired legs or the pooled data of both legs, were correlated with either their subjective functional outcomes or their maximal heel raise heights, and a correlation between the symmetry ratios of their fascicles and the functional outcomes was also found. These results reveal the morphomechanical adaptations that occur in legs that have undergone an Achilles rupture and clarify the relationships between such morphomechanical alterations and both objective and self-estimated functional abilities.

Our first findings with regard to muscle morphologies in a relaxed muscle condition were our observations of decreases in fascicle length and muscle thickness in the medial gastrocnemius muscles of the participants within the first six months after an Achilles repair. These findings were consistent with observations of disuse muscle atrophy caused by immobilization found in subjects demonstrating a short fascicle length of the vastus lateralis in the thigh following an isolated unilateral fracture of the femur (Bleakney and Maffulli, 2002). These decreases of the fascicle length may clinically translate to there being alterations in the gastrocnemius muscle length required to either produce the full range of joint motion (i.e., the muscle excursion levels) or maintain an optimal sarcomere length at a neutral position of the joint angle in the participants following tendon rupture and subsequent immobilization (Burkholder and Lieber, 1998). Furthermore, fascicle length decreases may be detrimental in terms of generating muscle peak power at a higher velocity (Lichtwark and Wilson, 2008). Previous studies have shown that there were increases in the lengths of human Achilles tendons post-rupture (Agres et al., 2015) and decreases in the number of sarcomeres and muscular length of the calf following surgical elongation of the tendo calcaneus in the cat (Tardieu et al., 1979). Therefore, our observations of muscle morphological alterations raise an important question as to whether patients who have experienced an Achilles rupture may suffer from chronic and obstinate gastrocnemius muscle shortening. It is worth mentioning that there is still significant time for continued healing of the tendon to occur, and as such one would expect biomechanical properties to improve. Our results indicate that assessments of fascicle length or muscle thickness should be integrated into regular assessments undertaken during patient rehabilitation after an Achilles rupture.

Secondly, our results showed that there were decreases in the mechanical properties of the proximal aponeurosis, in addition to showing a greater average pennation angle at 90% MVIC in the repaired legs. Our results further indicate that there were structural or compositional changes in the proximal aponeurosis of the medial gastrocnemius post-Achilles rupture. These findings imply that, in the repaired leg, there is (1) increased compliance, i.e. larger strains would require increased activation in the plantar flexor muscles and hence invoke less efficiency in the myotendinous system to maintain symmetrical motion with the opposite limb (McNair et al., 2013) and (2) changes to fascicle behaviors including a greater increase of the pennation angle during muscle contractions, which was confirmed by our observations of pennation angles at 90% MVIC. In addition, because the cosine component of the pennation angle determines the mechanical effectiveness of muscle force transmitted to the tendinous tissue (Kawakami et al., 1998), our results would imply that, in repaired legs, decreases in muscle efficiency due to angulation effects of the pennation may possibly become obvious when the force level is raised from a mild to submaximal isometric contraction. Our above findings collectively show that there are morphomechanical disadvantages in the medial gastrocnemius muscle following an Achilles rupture and immobilization. The above findings highlight the need for early mobilization and weight-bearing exercises to induce compensatory responses or preserve the status of the morphomechanical properties of the aponeurosis after an Achilles rupture.

Correlation analyses demonstrated that there are relationships between (1) the morphomechanical results of the pooled data (including aponeurosis mechanical properties, muscle thickness, and fascicle length) of the medial gastrocnemius and the maximal height of one-leg heel-raise tests of ankle plantarflexion (r ranged from 0.41 to 0.70), (2) the muscle morphologies in the repaired legs and the self-reported functional levels of the lower extremities and (3) the morphological symmetry of the fascicle lengths and the functional levels. Those first relationships imply that the above-discussed morphomechanical alterations involving a low peak muscle force and a great elongation of the tendinous tissue together bring about a decreased range of active force production and a lower fraction of effective torque in ankle plantarflexion during heel raising. A previous study has shown negative correlations between the side-to-side differences in heel-raise heights and Achilles tendon lengths at 6- and 12-month evaluations after an Achilles rupture (Silbernagel et al., 2012). It is possible that the length of the Achilles tendon affects the heel raise height through similar mechanisms to those found in our study. The correlations respectively between (1) the muscle morphologies (pennation angle and fascicle length) and LEFS-TC scores and (2) between the symmetry ratios of the fascicle lengths and the LEFS-TC scores ($r = -0.92$) indicated, firstly, that the pennation angle reflecting muscle size partially represents the recovery of functional level in the lower extremities postsurgery (Psatha et al., 2015). Secondly, the negative correlations regarding fascicle length in the repaired legs and the symmetry ratios for the fascicle lengths with the LEFS-TC scores implied that, in the repaired legs, a thickness reduced muscle with a longer fascicle length could intimate a lower pennation angle than in their counterparts and, therefore, was negatively associated with a lower functional level. Our results comprehensively demonstrate that muscle morphologies can be seen as clinical outcomes with the goal of minimizing calf activation deficits after an Achilles rupture and support the validity of the heel raise tests and LEFS-TC scores. Collectively, the clinical implications of our correlation results include the conclusion that medical personnel need to consider morphomechanical alterations in the calf muscle when dealing with any functional deficits observed after an Achilles rupture. It is recommended that future studies perform regular morphomechanical evaluations after Achilles tendon repairs to investigate the effects of types of postsurgical immobilization (cast vs. early mobilization) and structural restoration in the medial gastrocnemius muscle.

Our insignificant results included the finding that pennation angles in a relaxed muscle condition were similar between the repaired and non-injured legs. Possible mechanisms that can offset the negative effect of atrophy on pennation angle in a muscle with a repaired tendon cannot be identified in this study. The methodological limitations that cause systematic error of measurements in this study and involved ultrasound-based testing were not minimized, including not determining the following variables: tendon resting length, displacement of the axis of rotation at the ankle, displacement of the ultrasound probe in relation to the myotendinous unit (or skin), rotational movements of the anatomical references and calculating moment arms individually during a ramped isometric plantarflexion (Arampatzis et al., 2005, Seynnes et al., 2015). Additionally, whether the medial gastrocnemius muscles in both legs were in the same slack position was not assessed or confirmed. The limitations of this study also include its retrospective study design, small sample size, and the population with a wide range of age (20–60) that was studied. In addition, due to technical limitations, comparisons between the stiffness of the Achilles tendon and the stiffness of the proximal aponeurosis could not be made via the ultrasonographic measurements taken in this study (Maganaris, 2002). Furthermore, changes in dynamic muscle morphology appear to depend on the contraction types involved (Barber et al., 2013), and an isometric test environment may not provide optimal conditions to observe adaptations in all functional activities. In addition, the calculation of the joint kinetics and hence the force-length relationship of the tendon by a fixed external lever arm could be problematic if the point of force application under the foot is not constant for each contraction and each individual.

5. Conclusions

This study demonstrated there are differences in the morphomechanical characteristics of the medial gastrocnemius muscle of a leg in a relaxed muscle condition or during isometric contractions within three to six months of a unilateral Achilles tendon repair. Correlations between these morphomechanical characteristics and the maximal heel raise height or the self-estimated functional outcomes, as well as between fascicle symmetry and the functional outcomes, were also found. Our results indicated that morphomechanical alterations should be monitored for the purposes of functional restoration after an Achilles tendon rupture.

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Table 1. Acute Achilles tendon rupture postoperative rehabilitation program, modified from Strom and Casillas (2009).

Time	Schedule
Day 1 to week 1	Elevation, non-weight bearing, toe motion
Week 1 to week 2	Short leg cast with equinus, non-weight bearing, toe motion
Week 2 to week 3	Short leg cast with neutral ankle positions, non-weight bearing, toe motion, hip and knee muscle strengthening exercises.
Week 3 to Week 4	Short leg cast with neutral ankle dorsiflexion, non-weight bearing, toe motion, hip and knee muscle strengthening exercises.
Week 4 to week 6	Removable cast boot, partial-weight bearing with cane, physical therapy including massage, manual stretching and muscle lengthening of ankle plantarflexors, toe motion and ankle ROM exercise.
Week 6 to week 9	Removable cast boot, full weight bearing, physical therapy including joint mobilization, stretching, strengthening and essential cross training, such as agility.
Week 9 to week 12	Discontinue cast boot, full weight bearing and resistance training, physical therapy including proprioceptive and functional ankle recovery, and cross training.
Week 12 to week 16	Physical therapy program: return to sport phase, running and cross training.
After week 16	Full activities, home education that emphasizes stretching and warm-up

Table 2. Subject characteristics (N = 15).

Variables	
Age (y)	45.1 (10.6)
Gender (n): Male/Female	12/3
Repaired leg (n): Right/Left	8/7
Body height (cm)	169.2 (10.0)
Post-surgery period (months)	4.2 (1.1)
Body weight (kg)	78.6 (16.3)
Injury mechanism (n):	
Sports injury/Non-sports injury	13/2
LEFS-TC scores	74.0 (67.9–74.9)

Abbreviations: N: number of subjects. Age, body weight, body height and duration are presented as mean values, with the standard deviations (SD) in the parentheses. LEFS-TC data are given as median values, with the 95% confidence interval (CI) in the parentheses.

Table 3. Muscle morphological characteristics of the medial gastrocnemius muscle and the mechanical properties of its tendinous tissues in both legs of subjects with a unilateral Achilles repair.

Morphologies at the muscle belly in a resting state	Repaired leg		Non-injured leg		Wilcoxon signed ranks test
	Median	95% CI	Median	95% CI	
Fascicle length (cm)	4.30	(4.04–4.96)	5.20	(4.95–5.62)	0.016
Pennation angle (°)	22.36	(19.06 -o 25.57)	22.76	(20.05–25.10)	0.859
Muscle thickness (cm)	1.61	(1.51–1.75)	1.96	(1.76–2.09)	0.006
Maximal displacement of myotendinous junction (mm)	11.16	(8.14–12.25)	19.14	(11.66–21.58)	0.008
Maximal elongation of aponeurosis (mm)	2.11	(1.33–3.13)	1.27	(1.07–2.01)	0.307
Maximal tendon force (in N)	888.10	(628.90–1028.35)	1387.92	(978.64–1685.67)	< 0.001
Proximal aponeurosis stiffness (N/mm)	139.59	(115.02–171.21)	414.72	(306.50–462.43)	0.003
Maximal heel raise height (cm)	4.5	(3.51–5.69)	9.5	(8.55–10.20)	< 0.001

Results are presented as median values, with the 95% confidence interval (CI) in the parentheses.

Table 4. Pennation angles in the proximal aponeurosis to myotendinous junction at four levels of maximal voluntary isometric contraction (MVIC) in the repaired and non-injured legs.

	Repaired leg			**Sig.**	**Non-injured leg**			**Sig.**	**Wilcoxon signed rank test Sig. (2-tailed)**
	Median	**95% CI**	**Friedman test -Chi-Square**		**Median**	**95% CI**	**Friedman test -Chi-Square**		
Relaxed	18.91	(16.25–22.89)	30.44	< 0.001	18.85	(15.65–20.42)	33.80	< 0.001	0.173
30% MVIC	21.94	(19.85–25.52)			20.48	(17.64–22.85)			0.084
60% MVIC	24.59	(23.81–33.59)			23.62	(21.03–28.87)			0.060
90% MVIC	28.31	(26.36–35.96)			27.11	(24.97–32.83)			0.030

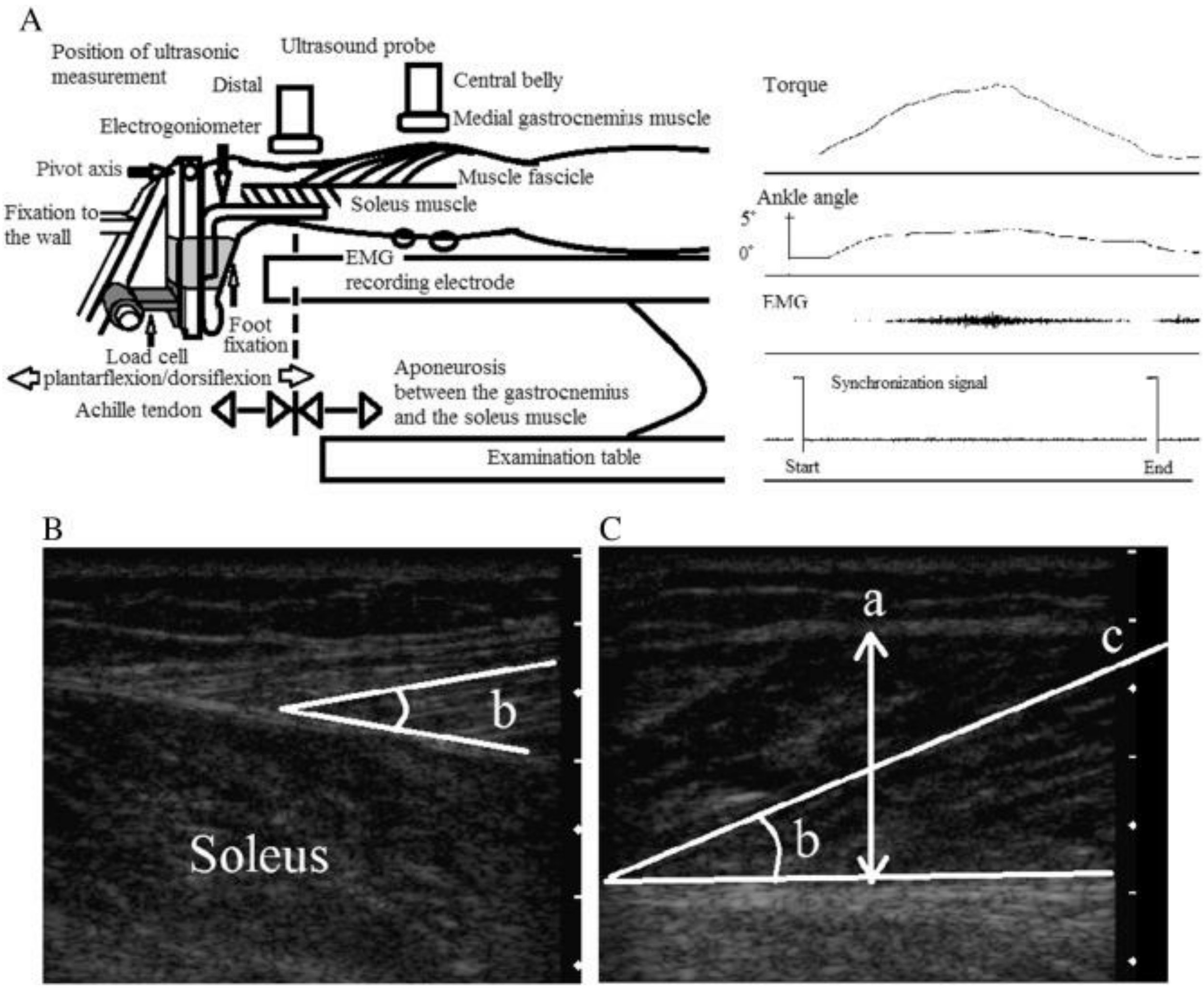

Figure 1 Subject setting and synchronized measurements of ankle plantarflexion torque, ankle plantarflexion angle, EMG of the tibialis anterior muscle and synchronization signals (A); ultrasonographic measurements of muscle morphologies at the myotendinous junction (B) and muscle belly (C): (a) muscle thickness (double arrow head), (b) pennation angle, (c) fascicle length (calculated as described by Kubo et al., 2003).

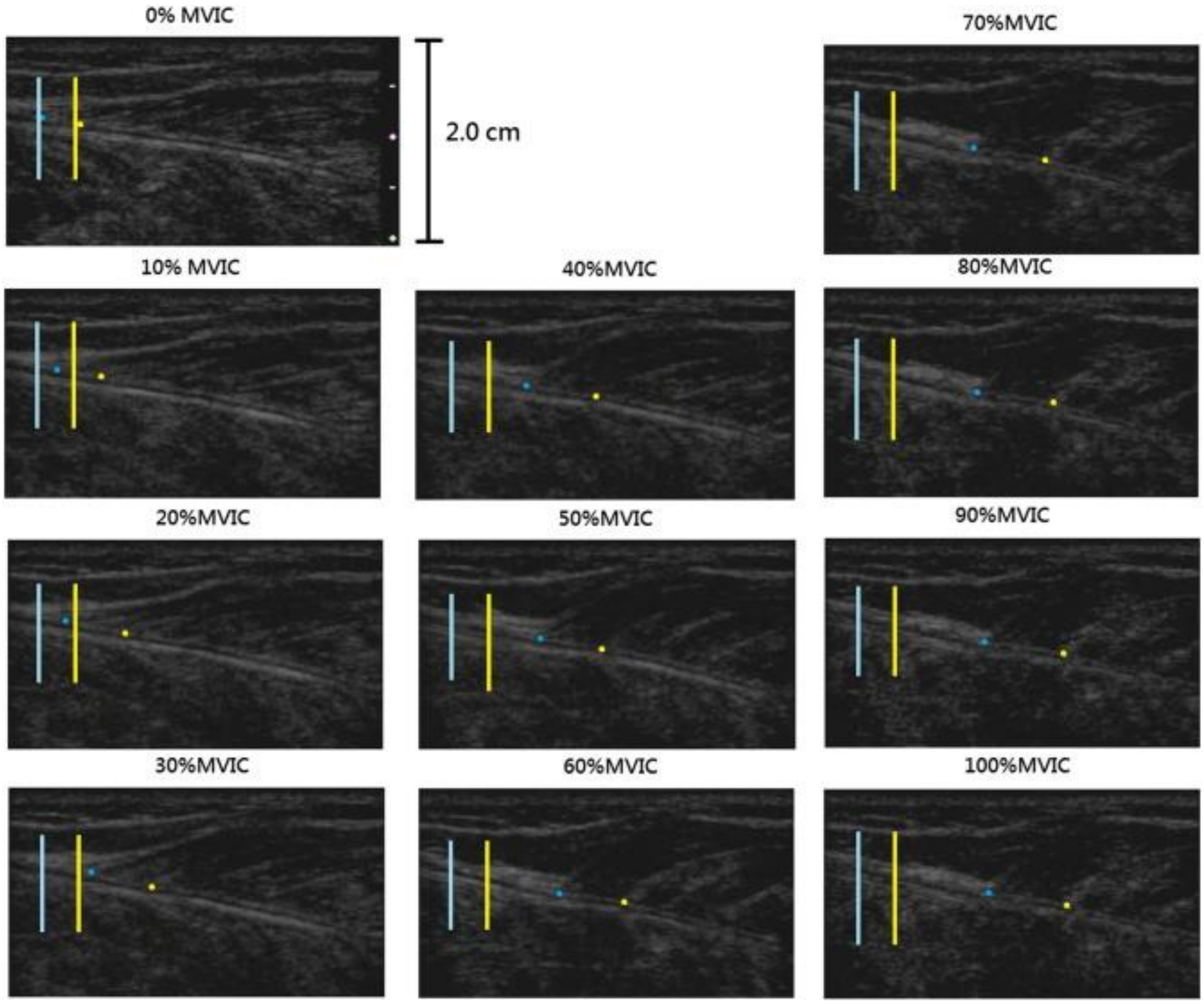

Figure 2. Ultrasonographic measurements of displacements of the myotendinous junction and proximal aponeurosis of the medial gastrocnemius muscle. Note the shift in the displacement of the myotendinous junction (blue dot) and the aponeurosis (yellow dot) to the right during the graded isometric contraction effort from rest (the lines) to 100% maximal contraction. Changes in the distances between the junction (blue dot) and the aponeurosis (yellow dot) were used to record the displacements of the proximal aponeurosis.

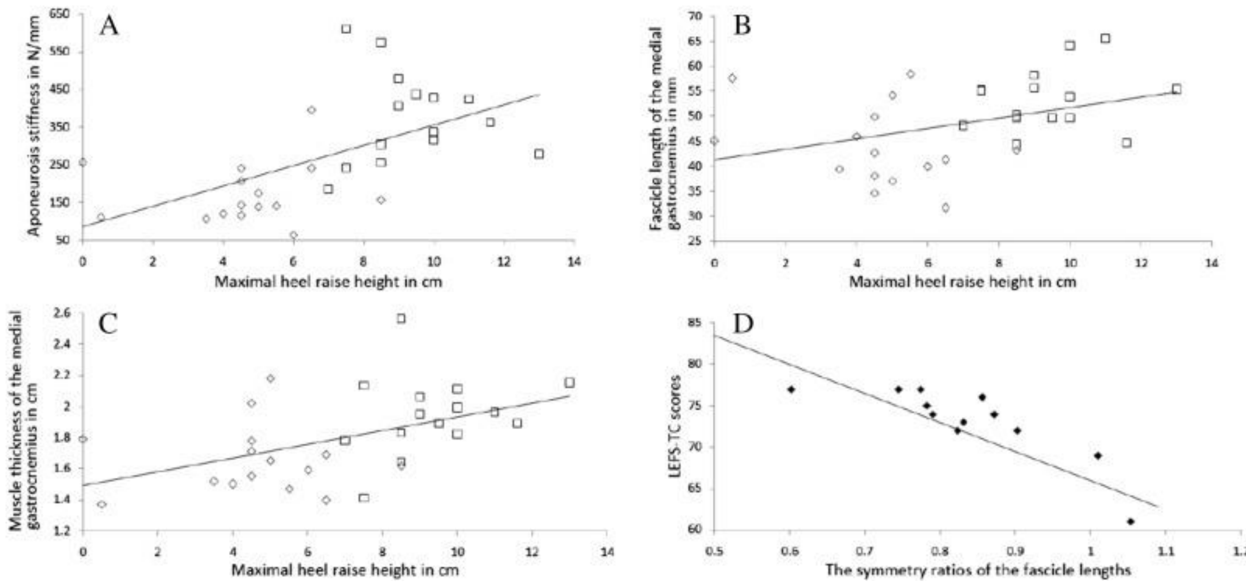

Figure 3. Correlations between the morphomechanical results and maximal heel raise heights, and between the symmetry ratios of the fascicle lengths and the LEFS-TC scores in subjects within 6 months post-surgery, repaired and control legs data were represented by different symbols (◊ and ☐ respectively). The aponeurosis stiffness values showed correlations with the heel raise heights (Spearman's rho = 0.70, $p < 0.001$) (A), the fascicle lengths (rho = 0.41, p = 0.024) (B), and the muscle thicknesses (rho = 0.53, p = 0.002) (C). The symmetry ratios of the fascicle lengths were correlated with the LEFS-TC scores (rho = − 0.92, $p < 0.001$) (D).