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Lecture

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

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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.

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

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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.

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

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