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Use of MRI for volume estimation of tibialis posterior and plantar intrinsic foot muscles in healthy and chronic plantar fasciitis limbs

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ABSTRACT

Background: Due to complexity of the plantar intrinsic foot muscles, little is known about their muscle architecture *in vivo*. Chronic plantar fasciitis may be accompanied by muscle atrophy of plantar intrinsic foot muscles and tibialis posterior compromising the dynamic support of the foot prolonging the injury. Magnetic resonance images of the foot may be digitized to quantify muscle architecture. The first purpose of this study was to estimate *in vivo* the volume and distribution of healthy plantar intrinsic foot muscles. The second purpose was to determine whether chronic plantar fasciitis is accompanied by atrophy of plantar intrinsic foot muscles and tibialis posterior.

Methods: Magnetic resonance images were taken bilaterally in eight subjects with unilateral plantar fasciitis. Muscle perimeters were digitally outlined and muscle signal intensity thresholds were determined for each image for volume computation.

Findings: The mean volume of contractile tissue in healthy plantar intrinsic foot muscles was 113.3 cm^3. Forefoot volumes of plantar fasciitis plantar intrinsic foot muscles were 5.2% smaller than healthy feet ($P = 0.03$, ES = 0.26), but rearfoot ($P = 0.26$, ES = 0.08) and total foot volumes ($P = 0.07$) were similar. No differences were observed in tibialis posterior size.

Interpretations: While the total volume of plantar intrinsic foot muscles was similar in healthy and plantar fasciitis feet, atrophy of the forefoot plantar intrinsic foot muscles may contribute to plantar fasciitis by destabilizing the medial longitudinal arch. These results suggest that magnetic resonance imaging measures may be useful in understanding the etiology and rehabilitation of chronic plantar fasciitis.

1. Introduction

Although plantar fasciitis (PF) is an injury of considerable consequence to the individual and the health care system, its aetiology is not well understood. Individuals suffering from PF experience heel pain upon weight-bearing that is severe in the morning (Young et al., 2001). Amongst the American population, the occurrence of PF is widespread, affecting more than 2 million individuals every year (Pfeffer et al., 1999). In the year 2007, the economic burden of PF on the United States health care system was estimated at $192 to $376 million (Tong and Furia, 2010). Despite the substantial encumbrance and cost of PF, the injury mechanisms of PF remain speculative. Generally, it is believed that PF results from excessive and/or repetitive loading of the plantar fascia and there are a multitude of factors which may contribute to such loading (Warren, 1990; Wearing et al., 2006).

It has been postulated that muscle weakness may be a potential cause of chronic plantar fasciitis (Chandler and Kibler, 1993; Wearing et al., 2006). Studies have shown that in a load-bearing limb, there are both passive and active mechanisms that support the medial longitudinal arch. Support is achieved passively by a tensioned plantar fascia, and actively by participation of the plantar intrinsic foot muscles (PIFM) and tibialis posterior (TP) muscle (Fiolkowski et al., 2003; Headlee et al., 2008; Kitaoka et al., 1997; Mann and Inman, 1964; Wong, 2007). Therefore, muscle weakness may prolong the healing process by putting added stress onto the already compromised plantar fascia. However, only two studies have examined how muscle properties are changed under the stress of chronic plantar fasciitis symptoms. These studies indicate that plantar fasciitis may be associated with a reduction in plantar flexor toe strength (Allen and Gross, 2003) and plantar flexor ankle strength (Kibler et al., 1991). Previous studies have suggested a cause and effect relationship between atrophy and PF, but it is also possible that atrophy may develop secondary to plantar fasciitis, particularly in chronic cases. Whether atrophy develops prior to PF onset or secondary to chronic PF, the duration of the injury can be prolonged when muscle function is compromised. The combined results of these

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studies suggest that there may be muscle atrophy with plantar fasciitis, but no data exists to confirm this notion.

The ten plantar intrinsic foot muscles (PIFM) are complex from an anatomical standpoint, making them a difficult research entity *in vivo* and *in vitro*. Surface access to the intricately arranged PIFM is restricted by the tarsal and metatarsal bones on the dorsal aspect of the foot, and by the fat and plantar fascia from the plantar aspect. As a result, only a small collection of studies have reported the architecture of these muscles, and these studies are primarily cadaveric in nature (Kura et al., 1997; Lachowitzer et al., 2007; Ledoux et al., 2001; Silver et al., 1985). Furthermore, it is not known whether there are changes in PIFM muscle size due to chronic overuse injuries, such as chronic plantar fasciitis. However, the availability of magnetic resonance imaging (MRI) provides an opportunity to research the PIFM *in vivo*, non-invasively and repetitively over time.

Therefore, the purpose of this study was twofold: 1) to determine the volume and distribution of PIFM within a healthy foot by analyzing MRIs spanning the entire length of the foot; and 2) to determine whether chronic plantar fasciitis is accompanied by atrophy of PIFM and the TP muscle. It was hypothesized that in comparison to healthy contralateral limbs, PF limbs would exhibit smaller PIFM volumes in the rearfoot and forefoot, and smaller TP volumes. In this study, the term atrophy was defined as a reduction in muscle volume in a given individual's limb in comparison to the contralateral limb.

2. Methods

2.1. Participants

Individuals between 30 and 60 years of age with chronic unilateral plantar fasciitis were recruited for this study. A call for research subjects was made to the public by posting flyers in the local community (footwear retailers and medical clinics), and an online press release was made by the university news and media office. Participants were included if they experienced: plantar heel pain on most days of the week, severe heel pain in the morning at least five times, and had pain upon palpation of the plantar heel. Participants were screened for MRI safety, answered 'no' to all questions of the Physical Activity Readiness Questionnaire, and gave informed consent to this study, which was approved by the University Institutional Review Board. Since it is believed that high-arched feet have a different plantar fasciitis injury mechanism than normal and low arched feet, individuals with a high-arch foot type were excluded (standing arch ratio 1.5 SD above the laboratory mean (Williams and McClay, 2000) or a foot posture index >1.5 SD of reported means (Redmond et al., 2006, 2008). Additional exclusion criteria included: symptomatic for less than three months, local steroid injection within the last 2 months, arthritis in the lower extremities, systemic conditions (e.g. arthritis and diabetes), local traumatic injury, neurological disorders, myopathies, local cardiovascular disorder, local infections and tumors, pregnancy or a body mass index >35 kg m^{-2}.

Eight PF individuals (7 females) qualified and consented to participate (mean (SD) age: 44.9 (8.4) years, height: 165.1 (8.0) cm, body mass: 75.6 (12.7) kg). Participants were symptomatic for an average (SD) of 3.0 (3.7) years (range: 0.4–10.0). PF feet and healthy feet were not different in their morphology as assessed by the weight-bearing arch ratio and foot posture index (Table 1). Participants rated their level of functional impairment using a Revised Foot Function Index (Budiman-Mak et al., 2006) (mean (SD): pain: 6.5 (3.9); stiffness: 3.6 (4.2); disability: 10.1 (9.8); activity limitation: 5.0 (4.4); and social issues: 2.6 (3.0)).

2.2. Protocol

Foot and leg MRIs were taken with a 1.5 T MR system (Espree, Siemens AG, Munich, Germany). Foot images were acquired using a four channel head coil positioned in the magnet's isocenter. Participants were positioned supine on the table with the ankle oriented in 45° of plantarflexion inside the coil. To reduce movement artifact during image acquisition, the foot, ankle, and knee were stabilized with sandbags and cushions. Care was taken to not deform the soft tissue from its natural non-weight-bearing shape. Frontal, sagittal, and transverse localizer images were acquired to confirm foot positioning and subjects were repositioned when necessary. T1 weighted images of the entire length of the foot were acquired perpendicular to the plantar aspect of the foot using a spin-echo sequence (repetition time = 500 ms, echo time = 16 ms, averages = 3, slice thickness = 4 mm, gap between slices = 0 mm, field of view = 120 × 120 mm, flip angle = 90°, matrix = 512 × 512). The data acquisition time for each foot was approximately 25 min.

Table 1
Mean (SD) anthropometric measures of the healthy and plantar fasciitis feet. The *P*-values are provided for a paired *t*-test.

Variable	Healthy	Plantar fasciitis	*P* value
Arch ratio	0.313 (0.025)	0.316 (0.023)	0.85
Foot posture index	5.0 (3.1)	4.8 (3.9)	0.89

To acquire leg images, participants were positioned supine on the table with knees straight and feet taped together. Sandbags were placed at the medial and lateral borders of the legs to further minimize motion artifact. Two six-element pre-amplified flexible coils were wrapped around the participant's lower extremities and four three-element pre-amplified coils in the table were activated. For each leg, images were acquired from the knee joint to the malleoli. Images were taken at a perpendicular direction with respect to the patient table (repetition time = 500 ms, echo time = 16 ms; field of view = 210 × 210 mm, matrix = 512 × 512, averages = 2, thickness = 4 mm, gap = 0 mm). Due to the length of the legs, image acquisition required two passes; the distal leg was imaged first and then the proximal leg. The data acquisition time for one leg was approximately 50 min. DICOM image files were saved onto transportable media for data reduction.

2.3. Data reduction

A single researcher used interactive custom software programmed in Matlab (Mathworks Inc., Natick, USA) to quantify muscle cross-sectional area (CSA) for each participant's image set (Fig. 1), in the same manner as Hasson et al. (2011) (an adaptation of Kent-Braun et al., 2000). Over 150 images were processed as practice before the study data were formally processed. The researcher was blinded as to whether the image set was acquired from a PF or healthy limb. Examining each grayscale MRI, PIFM perimeters were outlined and, wherever possible, non-contractile tissues such as bone, tendon, fat, connective tissue, nerve and blood vessels were excluded (Fig. 2a). To facilitate the identification of the various anatomical structures, the user could zoom and toggle between neighboring images. While the extensor digiti brevis muscles of the dorsal foot were excluded, the dorsal interossei muscles could not be excluded due to their small size.

For each image, lower and upper muscle pixel signal intensity thresholds were assigned (Fig. 1). Muscle thresholds were not held constant across an image set in recognition of signal intensity changes due to the gradient of the main magnetic field, and changes in magnetic field related to body segment distance from each coil. The lower panel of Fig. 1 provides a plot of the frequency distribution of pixel intensities within the corresponding MRI (each MRI was cropped and zoomed for processing to expand the relevant area). Three vertical bars indicate the user-selected low threshold, the most frequent pixel intensity, and the user-selected high threshold, respectively. The assignment of muscle pixel intensities improved the muscle volume estimation by