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Effect of Achilles tendon loading on plantar fascia tension in the standing foot

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Abstract

Background. The plantar fascia, which is one of the major arch-supporting structures of the human foot, sustains high tensions during weight-bearing. A positive correlation between Achilles tendon loading and plantar fascia tension has been reported. Excessive stretching and tightness of the Achilles tendon are thought to be the risk factors of plantar fasciitis but their biomechanical effects on the plantar fascia have not been fully addressed.

Methods. A three-dimensional finite element model of the human foot and ankle, incorporating geometrical and material nonlinearity, was employed to investigate the loading response of the plantar fascia in the standing foot with different magnitudes of Achilles tendon loading.

Findings. With the total ground reaction forces of one foot maintained at 350 N to represent half body weight, an increase in Achilles tendon load from (0–700 N) resulted in a general increase in total force and peak plantar pressure at the forefoot of up to about 250%. There was a lateral and anterior shift of the centre of pressure and a reduction in the arch height with an increasing Achilles tendon load as a result of the plantar flexion moment on the calcaneus. From the finite element predictions of simulated balanced standing, Achilles tendon forces of 75% of the total weight on the foot (350 N) were found to provide the closest match of the measured centre of pressure of the subject during balanced standing. Both the weight on the foot and Achilles tendon loading resulted in an increase in tension of the plantar fascia with the latter showing a two-times larger straining effect.

Interpretation. Increasing tension on the Achilles tendon is coupled with an increasing strain on the plantar fascia. Overstretching of the Achilles tendon resulting from intense muscle contraction and passive stretching of tight Achilles tendon are plausible mechanical factors for overstraining of the plantar fascia.

Keywords: Finite element analysis; Plantar aponeurosis; Fasciitis; Cadaver; Strain; Night splints

1. Introduction

The plantar aponeurosis (fascia), which originates from the medial tubercle of the calcaneus and inserts into the phalanges through a complex network of fibrous tissue (Hicks, 1954) is one of the major stabilising structures of the longitudinal arch of the foot. Cadaveric studies revealed that release of the plantar fascia decreased arch height, confirming the arch-supporting function of the plantar fascia (Kitaoka et al., 1997; Murphy et al., 1998).

Insertional plantar fasciitis, which is common in athletes as well as the general population (Cornwall and McPoil, 1999; Warren, 1990), usually associates with a chronic painful syndrome at the inferior heel region. Excessive stretching, repetitive and abnormal stress induced in the plantar fascia and its calcaneal insertion may cause inflammation and injury, which are thought

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to be the major causes of plantar fasciitis (Cornwall and McPoil, 1999; Warren, 1990). Conditions which predispose the plantar fascia to increased tension during weight-bearing such as excessive pronation, flat or high-arched foot structures and tight Achilles tendon are often suggested as implicating factors of plantar fasciitis (Warren, 1990).

Conservative treatment such as anti-inflammatory medication, stretching and strengthening exercise and foot orthoses has been used effectively to alleviate the painful syndrome of plantar fasciitis (Barry et al., 2002; Pfeffer et al., 1999; Probe et al., 1999). Stretching exercise and dorsiflexion night splints are often prescribed to help relieve the Achilles tendon tension with an attempt to reduce arch deformation, excessive pronation, rearfoot valgus and the tension of the plantar fascia. The dorsiflexion night splint was first described for use in the treatment of plantar fasciitis by Wapner and Sharkey (1991) and has been proven to be beneficial by several prospective and randomised control studies (Barry et al., 2002; Probe et al., 1999).

Despite the success of Achilles tendon stress relief for treatment of plantar fasciitis, the biomechanical relationship between Achilles tendon loading and tension on the plantar fascia has not been well documented. A larger number of cadaveric studies (Crary et al., 2003; Donahue and Sharkey, 1999; Kitaoka et al., 1997; Thordarson et al., 1995) and computational analyses (Cheung et al., 2004; Gefen, 2002; Giddings et al., 2000; Kim and Voloshin, 1995) have focused on the biomechanical response of the plantar fascia under different loading and supporting conditions and the biomechanical consequences of fasciotomy. Because of the difficulties and invasive nature of in vivo measurements of Achilles tendon tension (Finni et al., 1998), the biomechanical effect of varying Achilles tendon loading on plantar fascia has only been investigated by cadaveric studies. Thordarson et al. (1995) documented the arch-deforming effect of the Achilles tendon loading and the arch-supporting mechanism of the plantar fascia with toe extension via a 3D movement analysis on cadavers. Carlson et al. (2000) measured an increased plantar fascia strain with increasing loading on the Achilles tendon and with toe extension under static loading conditions of the foot. Erdemir et al. (2004) found a positive correlation between plantar fascia tension and Achilles tendon force during simulations of the stance phase of gait in a cadaver model.

Although cadaveric studies (Carlson et al., 2000; Erdemir et al., 2004) have been done to investigate the effect of Achilles tendon loading on the loading response of the plantar fascia, these studies were subjected to certain limitations. For instance, physiological loading condition was not simulated by Carlson et al. (2000) because the body weight on the foot was not considered. Erdemir et al. (2004) measured the tension of the plantar fascia during simulated normal walking using a dynamic cadaveric model without a strict control on the effects of other extrinsic muscle forces, ground reaction forces and ankle–foot position. Therefore, their cadaveric simulation cannot provide a sensitivity analysis on the effects of Achilles tendon tension on the loading response of the plantar fascia. In this study, a 3D finite element (FE) foot model was employed to quantify the biomechanical effect of varying Achilles tendon loading on the plantar fascia, longitudinal arch deformation and plantar pressure distribution of the standing foot.

2. Methods

A geometrically accurate FE model of the human foot and ankle was developed from 3D reconstruction of coronal Magnetic Resonance (MR) images of 2 mm intervals from the right foot of a normal male subject of age 26, height 174 cm and weight 70 kg in the neutral position (Cheung et al., 2005). The neutral foot position (Wu et al., 2002) of the supine lying subject was maintained by a custom ankle–foot orthosis during the MR scanning. The undeformed arch height of the subject was 55 mm during upright sitting. The arch height was defined as the height of the medial navicular cortex to the ground support. The model took into account the actual 3D ankle/foot geometry and nonlinearities from material properties, large deformations and interfacial slip/friction conditions. The FE model (Fig. 1) consisted of 28 bony segments embedded in a volume of encapsulated soft tissue. A total number of 72 ligaments and the plantar fascia were included and defined by connecting the corresponding attachment points on the bones. Except the phalanges were connected with cartilaginous structures, the interactions between the rest of the bony structures were defined as contacting elastic bodies to allow relative bone movements. Frictionless surface to surface contact behaviour was defined between the contacting bony structures. Contact stiffness resembling the softened contact behaviour of the cartilaginous layers (Athanasiou et al., 1998) was prescribed between each pair of contact surface.

The foot bones (Nakamura et al., 1981), ligaments (Siegler et al., 1988), plantar fascia (Wright and Rennels, 1964) and cartilaginous structures between the phalanges (Athanasiou et al., 1998) were idealised as homogeneous, isotropic and linearly elastic (Table 1) while the encapsulated soft tissue (Lemmon et al., 1997) was defined as hyperelastic. A second-order polynomial strain energy potential (ABAQUS v6.4, Hibbitt, Karlsson & Sorensen, Inc., Pawtucket, RI, USA) was adopted with the form

$$U = \sum_{i+j=1}^{2} C_{ij}(\bar{I}_1 - 3)^i(\bar{I}_2 - 3)^j + \sum_{i=1}^{2} \frac{1}{D_i}(J_{\mathrm{el}} - 1)^{2i} \qquad (1)$$