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Experimental evidence supporting isometric functioning of the extrinsic toe flexors during gait

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ABSTRACT

Background: The extrinsic toe flexors, flexor hallucis longus and flexor digitorum longus, play an important role in stabilizing the longitudinal arch and supporting high forefoot loads during the stance phase of gait. It was hypothesized that these muscles function isometrically during stance, a strategy thought to provide efficient energy transfer across adjoining body segments, but one for which there is little direct experimental evidence *in vivo* or *in situ*.

Methods: Eight lower extremity cadavers were loaded into a robotic apparatus that simulates the kinematics and extrinsic muscle activity of the foot and distal tibia during the stance phase of gait. Instantaneous tendon excursions and forces of the extrinsic toe flexors, as well as plantar pressure distributions during stance, were measured under two muscle control strategies: (1) force feedback control, where tendon forces were matched to forces predicted from normal electromyographic patterns and (2) isometric displacement control, where the representative myotendinous junction was held in a constant location.

Results: Tendon excursions of the flexor hallucis longus (7.18 (1.75) mm) and flexor digitorum longus (6.32 (1.74) mm) under force feedback control were small relative to optimal muscle fiber length (13.6% and 14.2%, respectively). Instantaneous tendon forces and plantar pressure variables were not different ($P =$ 0.112–0.912) between the two different muscle control strategies for either muscle.

Interpretation: These findings suggest that the extrinsic toe flexors function isometrically during the stance phase of gait *in vivo*.

1. Introduction

The human foot serves as the interface between the lower limb and the ground during locomotion. The musculoskeletal structure of the foot has evolved in such a way that allows for an efficient distribution of ground reaction forces during walking. The total force acting upon the forefoot during the push-off phase of gait is approximately 120% of body weight (Hayafune et al., 1999; Hetherington et al., 1992), with the first and second rays being the most heavily loaded during normal locomotion (Jacob, 2001). Flexor hallucis longus (FHL) and flexor digitorum longus (FDL) are the extrinsic muscles directly responsible for flexion of the hallux and lateral four rays, respectively. In-dwelling electromyographic (EMG) recordings show that these muscles are activated during mid-stance, with activity terminating just after toe off (Perry, 1992).

Extrinsic plantarflexors, including FHL and FDL, have been shown to play a significant role in stabilizing the longitudinal arch (Thordarson et al., 1995). Simulated loss of FHL and FDL function has been shown to significantly increase loading under the metatarsal heads and decrease loading beneath the toes (Ferris et al., 1995). Other active and passive components of toe flexion also have a significant effect on the load distribution across the forefoot at terminal stance (Hamel et al., 2001). Although these muscles clearly contribute to the stabilization and balancing of forefoot loading, there is little direct experimental evidence examining the mechanisms by which these muscles do so, *in vivo* or *in situ*.

The architectural properties of a muscle are generally considered to be a strong predictor of how the muscle functions (Lieber and Ward, 2011). The ratio of muscle fiber length to muscle length is small for both the FHL and FDL (0.16 and 0.20, respectively; Ward et al., 2009), indicating that these muscles shorten minimally during contraction, suggesting isometric or near-isometric function. The two muscles also exhibit similar EMG patterns (Perry, 1992) and physiologic cross-sectional areas (PCSA; Ward et al., 2009), in addition to both being bi-pennate and multi-articular. The many similarities suggest that these anatomic synergists may also be

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under the same neuromuscular input and control strategy during locomotion.

A previous study in our laboratory found that isometric function of the FHL during dynamic simulations of the stance phase of gait in cadavers produces normal joint reaction forces (JRFs) at the first metatarsophalangeal (MTP) joint (Kirane et al., 2008a, 2008b). It was also found that experimental conditions designed to mimic constriction and swelling at that muscle's entrance to the fibro-osseus tunnel resulted in high compressive forces at the first MTP, suggesting a plausible etiology for hallux rigidus (Kirane et al., 2008b). Albeit informative, this study was limited by a small sample size, and did not examine the function of the FDL or the role that different muscle control strategies might play in altering plantar pressure distributions.

The purpose of this study was to further investigate the mechanics of the FHL and FDL using a high-fidelity dynamic cadaver simulation of gait. This study employed the Robotic Dynamic Activity Simulator (RDAS), the capabilities of which have been extensively tested and validated in the past (Hoskins, 2005; Sharkey and Hamel, 1998), to address the hypothesis that the FHL and FDL function isometrically during the load bearing portion of the gait cycle. This would be evidenced by functionally appropriate tendon forces and plantar pressure distributions under simulated isometric muscle function.

2. Methods

2.1. Specimen preparation

Eight non-paired fresh frozen lower extremity cadaver specimens (Age range: 47–84 yrs; 5 male, 3 female; 6 left, 2 right) were used in this study. The tibia of all specimens was cut approximately 24 cm above the sole of the foot and all soft tissue proximal to the malleoli was removed while preserving the full lengths of the tendons of the extrinsic foot muscles. A metallic cup was fixed to the proximal end of the cut tibia with bone cement to link the specimen to the RDAS (Fig. 1).

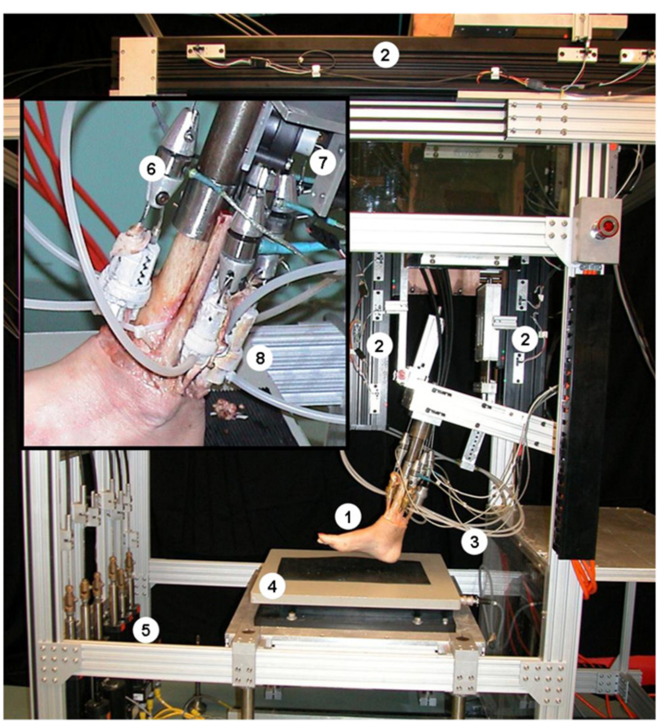

Fig. 1. Robotic dynamic activity simulator with specimen loaded into the chassis: (1) cadaver specimen (2) three kinematic linear actuators (3) liquid nitrogen tubes (4) force plate (5) six kinetic linear actuators (6) load cell (7) displacement transducer (8) clamp tendon junction.

2.2. RDAS

The RDAS is a second generation gait simulator consisting of a main chassis supporting a specimen carriage controlled by three linear actuators that reproduce dynamic sagittal plane kinematics of the tibia based upon measurements from live subjects of similar size, but at velocities scaled to 1/20 of those occurring *in-vivo* (Fig. 1). Fixed to the chassis is a force plate (AMTI, Watertown, MA, USA), the top of which serves as the walking surface for simulations. A separate collection of six linear actuators reproduce lower extremity muscle function during the simulations. Three muscles are controlled individually: FHL, FDL, and tibialis posterior, and three muscles are controlled as a group: triceps surae (gastrocnemius and soleus), peronei (peroneus longus and brevis) and extensors (tibialis anterior, extensor digitorum longus, extensor hallucis longus). Cryo-clamps are fixed to the proximal end of each stripped tendon or tendon group (i.e., the clamp-tendon junction, CTJ) and then purged with liquid nitrogen to form a rigid interlock between the tissue and serrations of the clamp (Sharkey et al., 1995a, 1995b). Coupled to each CTJ was a load cell (A.L.Design, Buffalo, NY, USA), to measure instantaneous tendon forces, and a displacement transducer (Unimeasure, Corvallis, OR, USA), to measure tendon excursions.

In the present experiment, care was taken to clamp the tendons of FHL and FDL along their former myotendinous junctions to preserve the material behavior of the entire tendon length and accurately reflect the consequences of muscular contractions. Changes in the proximal–distal position of the clamp were assumed to be reasonable representations of displacements at the myotendinous junction *in vivo*.

The instantaneous load in each musculo-tendinous unit was matched to target forces derived from EMG data (Perry, 1992) and physiologic cross sectional area (PCSA; Friederich and Brand, 1990) of the involved muscles. More in-depth descriptions of the RDAS, including its capabilities, validation, and control algorithms are presented elsewhere (Kirane et al., 2008a, 2008b; Sharkey and Hamel, 1998).

2.3. Experimental protocol

Once fixed into the specimen carriage with all extrinsic tendons fixed in freeze-clamps, a series of set-up trials were conducted to match dynamic ground reaction forces in the model to those measured in the subject whose kinematic data were used to drive the model's tibial kinematics. To do this, the height of the specimen carriage was iteratively lowered until the first peak of the vertical ground reaction force profile closely matched that of the subject, after which the plantar flexor force curves were iteratively increased in concert, while maintaining their proper relational magnitudes, until the second propulsive peak of the vertical ground reaction force also matched that recorded for the live subject. After establishing proper biomechanical behavior, all parameters driving the model were held constant except those experimentally manipulated to address our hypothesis concerning the FHL and FDL.

Following the set-up trials, each specimen was subject to three separate conditions: (1) force feedback control (FFC), where all six functional muscle units were matched to the target force profiles derived from EMG patterns, i.e. the baseline condition established in the procedures outline above; (2) isometric displacement control (IDC) of FHL, where CTJ of the FHL was held stationary; and (3) IDC of FDL, where the CTJ of the FDL was held stationary. Instantaneous tendon forces under IDC were solely a function of the kinematics and geometry of the foot as it progressed through the stance phase; the RDAS controller simply sought to seek constant position of the representative myotendinous junction irrespective of the forces carried in the tendon. The position at which the CTJ (representing the myotendinous junction) was held constant was determined by a trial and error process starting at the midpoint of the excursions measured in the initial FFC