Passive Engineering Mechanism Enhancement of a Flexor Digitorum Longus Tendon Transfer Procedure: A Cadaver Study

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Disclosures: None

ABSTRACT INTRODUCTION: Adult acquired flatfoot deformity (AAFD), the most common foot disorder in the United States (Gould et al. 1980, FAI), is characterized by collapse of the medial longitudinal arch, forefoot abduction, and hindfoot eversion. The primary cause of AAFD is posterior tibial tendon dysfunction (PTTD), a progressive condition typically affecting patients with a history of diabetes, hypertension, and/or obesity (Holmes and Mann 1992, FAI). Stage II PTTD, the model used in this study, is an intermediate stage characterized by rupture or advanced attenuation of the posterior tibial (PT) tendon, passively correctable forefoot abduction, and hindfoot valgus (Myerson 1996, JBJS). A standard treatment of stage II PTTD is a flexor digitorum longus tendon transfer (FDLTT) combined with a bony procedure, such as a medializing calcaneal osteotomy. Previous studies have shown that standard treatment is successful in providing symptomatic relief and functional improvement (Guyton et al. 2001, FAI); however, it does not restore physiologic muscle forces to the medial longitudinal arch (Rosenfeld et al. 2005, FAI).

A novel treatment to enhance FDLTT utilizes passive engineering mechanisms (PEM). Mardula et al. (2014, Hand) demonstrated that implanted PEMs (e.g. pulleys) can be used to enhance a tendon transfer procedure of the hand for improved function. The efficacy of utilizing a PEM as a dynamic force-scaling device in a FDLTT holds promise, but has not yet been established. The objective of this research study is to determine if a PEM-enhanced FDLTT will increase the force applied to the medial longitudinal arch compared to a standard FDLTT using a dynamic cadaveric flatfoot model. It is hypothesized that addition of a PEM will cause a lateral shift in gait cycle peak plantar pressure and center of pressure (CoP) and will increase mid- and hindfoot inversion, adduction, and plantar flexion compared to flatfoot and standard FDLTT conditions.

METHODS: Seven fresh-frozen cadaveric lower-limb specimens (6M, 1F, 67.6 ± 11.4 years, 75.0 ± 13.2 kg) were obtained. Baseline radiographic studies were performed and used to make diagnostic bony measures. A flatfoot (FF) model consistent with stage II PTTD was induced. Ligaments pathologically associated with PTTD were attenuated or transected (Deland et al., 2005, FAI). Specimens were cyclically loaded with physiologic forces for an average of 125,000 cycles at 2 Hz. Flatfoot radiographs and diagnostic bony measures were obtained for comparison (Sangeorzan et al. 1993, FAI). Specimens were mounted on a robotic gait simulator (RGS), which simulates the stance phase of gait by accurately reproducing in vivo vertical ground reaction forces, extrinsic muscle tendon forces, and tibia to ground kinematics. Specimens were randomly tested on the RGS under five conditions: FF (control), FDLTT, hyperFDLTT, PEM, and hyperPEM. In the FF condition, no force was applied to the PT tendon to simulate the musculotendinous degeneration characteristic of stage II PTTD. In the four treatment conditions, FDL muscle force was applied to the PT tendon as a proxy for a FDLTT to PT residuum procedure. In PEM conditions, a custom pulley was attached to the PT tendon posterior to the medial malleolus (Fig. 1). In hyper- conditions, FDL muscle force was increased to simulate in vivo hypertrophy following FDLTT (Rosenfeld et al. 2005, FAI). Three trials were recorded for each condition per specimen for a total of 105 trials. Foot bone kinematics were measured for each condition using an 8-camera motion capture system synchronized to the RGS and a 10-segment, 40-marker foot model. Plantar pressures and CoP were assessed with an RGS-integrated pressure mat system.

Independent RGS testing was completed to measure PEM force scaling. A load cell affixed between the pulley and tendon recorded the scaled force throughout stance phase. Five trials were collected for five of the seven specimens for a total of 25 trials.

For preliminary statistical analysis, a dependent t-test was performed to determine if diagnostic bony measures differed after inducing the FF model. A repeated measures ANOVA with the Bonferroni correction was performed to determine if biomechanical parameters differed between conditions. Significance was set at $p = 0.05$.

RESULTS: Preliminary findings indicate that mean diagnostic bony measure changes after inducing the FF model were statistically significant ($p = 0.03$) and are consistent with stage II PTTD. Over the second half of stance phase, the maximum FDL tendon force increased by 42.9 ± 7.9% due to PEM-enhancement (Fig. 2). A significant lateral shift in CoP from the FF condition was observed in the PEM condition at 25% and 50% stance phase ($p = 0.04$ and $p = 0.04$, respectively) and the hyperPEM condition at 90% stance phase ($p = 0.04$). A significant lateral shift in CoP from the FDLTT condition was observed in the PEM condition at 90% stance phase ($p = 0.02$). A significant lateral shift in CoP from the hyperFDLTT condition was observed in the hyperPEM condition at 90% stance phase ($p = 0.02$). No significant differences were observed in peak plantar pressure among conditions. More robust statistical analysis is in progress, including evaluation of kinematic findings.

DISCUSSION: The aim of this study was to establish the efficacy of utilizing a PEM as a force-scaling device in a FDLTT procedure. The addition of a PEM to FDLTT did increase the tendon forces transferred to the medial longitudinal arch, more closely restoring the physiologic PT forces when compared to FDLTT treatment alone. This improvement resulted in a significant lateral shift in CoP from the FF model, a change not observed after FDLTT treatment alone. These findings suggest that a PEM-enhanced FDLTT procedure may better correct stage II PTTD versus standard treatment. Further investigation is warranted to expand on this proof-of-concept study.

SIGNIFICANCE: Treatment of stage II PTTD remains a difficult clinical problem. Muscular imbalance following standard surgical treatment is a universal complication that has not been fully addressed. This study establishes PEM-enhancement as a potential solution. With more patients suffering from flatfoot deformity in the U.S. than any other foot condition, the potential for treatment innovation is significant.

ACKNOWLEDGEMENTS: Thanks to Matt Kindig, Tia Fogle, and Brian Cook for their important contributions to this study. Thanks to the Veterans Administration and University of Washington School of Medicine for funding.

IMAGES AND TABLES:

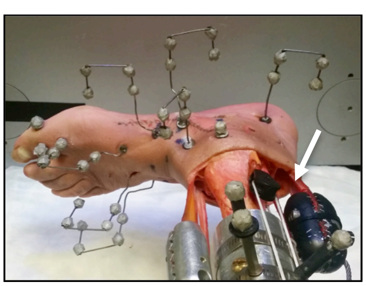

Fig. 1. Specimen mounted on RGS for testing with PEM (arrow).

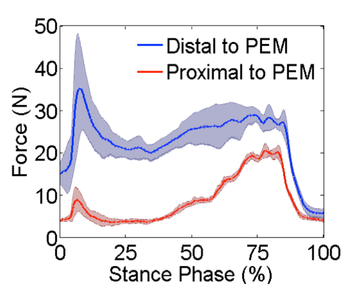

Fig. 2. Mean FDL force ± SD throughout stance phase distal and proximal to the pulley (25 trials, n = 5).

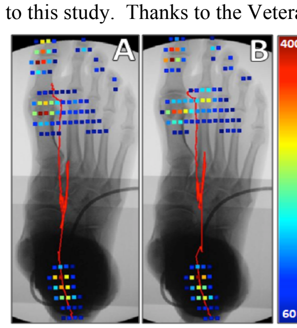

Fig. 3. Sample CoP (red line) and peak pressure (squares; kPa) for (A) FF and (B) PEM conditions normalized to AP radiograph illustrating lateral shift.