Comparison of Transfer Sites for Flexor Digitorum Longus in a Cadaveric Adult Acquired Flatfoot Model

Nicholas J. Vaudreuil,[1,2] William R. Ledoux,[1,3,4] Grant C. Roush,[1,3] Eric C. Whittaker,[1] Bruce J. Sangeorzan[1,4]

[1]RR&D Center of Excellence for Limb Loss Prevention and Prosthetic Engineering, VA Puget Sound, Seattle, Washington 98108, [2]School of Medicine, University of Washington, Seattle, Washington 98195, [3]Department of Mechanical Engineering, University of Washington, Seattle, Washington 98195, [4]Department of Orthopaedics & Sports Medicine, University of Washington, Seattle, Washington 98195

Received 10 May 2013; accepted 19 August 2013
Published online 21 September 2013 in Wiley Online Library (wileyonlinelibrary.com). DOI 10.1002/jor.22488

ABSTRACT: Posterior tibialis tendon (PTT) dysfunction (PTTD) is associated with adult acquired flatfoot deformity. PTTD is commonly treated with a flexor digitorum longus (FDL) tendon transfer (FDLTT) to the navicular (NAV), medial cuneiform (CUN), or distal residuum of the degraded PTT (rPTT). We assessed the kinetic and kinematic outcomes of these three attachment sites using cadaveric gait simulation. Three transfer locations (NAV, CUN, rPTT) were tested on seven prepared flatfoot models using a robotic gait simulator (RGS). The FDLTT procedures were simulated by pulling on the PTT with biomechanically realistic FDL forces (rPTT) or by pulling on the transected FDL tendon after fixation to the navicular or medial cuneiform (NAV and CUN, respectively). Plantar pressure and foot bone motion were quantified. Peak plantar pressure significantly decreased from the flatfoot condition at the first metatarsal (NAV) and hallux (CUN). No difference was found in the medial–lateral center of pressure. Kinematic findings showed minimal differences between flatfoot and FDLTT specimens. The three locations demonstrated only minimal differences from the flatfoot condition, with the NAV and CUN procedures resulting in decreased medial pressures. Functionally, all three surgical procedures performed similarly. Published 2013 by Wiley Periodicals, Inc. on behalf of the Orthopaedic Research Society. J Orthop Res 32:102–109, 2014.

Keywords: posterior tibial tendon dysfunction; flexor digitorum longus transfer; PTTD; FDL; gait simulation

Adult acquired flatfoot deformity is a common disorder characterized by collapse of the medial longitudinal arch, forefoot abduction, and hindfoot eversion.[1] Posterior tibialis tendon dysfunction (PTTD) is associated with adult acquired flatfoot deformity in both a chronic and a traumatic fashion,[2,3] although the exact role of the failure of the posterior tibialis tendon (PTT) is not completely known. The valgus deformity resulting from collapse of medial supporting ligaments leads to increased eversion of the calcaneus due to the position of the Achilles tendon lateral to the axis of rotation of the subtalar joint.[4] Degradation of the medial supporting ligaments over time results in a painful and visibly deformed flatfoot.[5]

The treatment of PTTD depends on the clinical stage. The model used in this study closely resembles Stage II PTTD, initially described by Johnson and Strom and later modified by Myerson,[6,7] as an intermediate stage characterized by a torn or attenuated PTT with flexible forefoot abduction and hindfoot valgus. Treatment of stage II PTTD usually involves a soft tissue repair, for example, Achilles lengthening or flexor digitorum longus (FDL) tendon transfer (FDLTT), and a bony procedure, such as a medializing calcaneal osteotomy (MCO).[8–10]

Our research interest lies in the manner in which the FDLTT is performed, specifically where the transected FDL will be attached. Multiple transfer sites can be utilized with the navicular, medial cuneiform, and distal residuum of PTT being the most common. Previous studies showed that navicular and the medial cuneiform have similar biomechanical effects when used as tenodesis points.[11] Conclusive evidence of advantages or disadvantages of different FDLTT sites has yet to be established. We aimed to study the kinetic and kinematic effects of FDLTT to the navicular, medial cuneiform, and distal residuum of the PTT by testing Stage II simulated cadaveric feet on a robotic gait simulator (RGS) during stance phase. We hypothesized that each of the FDLTT procedures would result in a lateral shift in peak pressure. We also hypothesized that the center of pressure (CoP) would shift laterally from the flatfoot to the surgical conditions and that there would be an increase in medial–lateral range of the CoP. Additionally, we expected joint kinematics to post-surgically reflect inversion, adduction, and plantar flexion. Our primary joints of focus were the talonavicular and naviculocuneiform. Finally, we hypothesized that no differences in plantar pressure, CoP, or joint kinematics would exist between surgical transfer sites.

METHODS

Seven fresh-frozen cadaveric lower limb specimens (2M, 5F, 78.9 ± 8.9 years, 69.4 ± 14.9 kg) were obtained from the University of Washington Department of Biological Structures and transected mid-tibia. Radiographs of the specimens loaded to 25% of the donor's body weight were used to measure initial calcaneal pitch angle (CPA), lateral talometatarsal angle (LTMA), talonavicular coverage angle (TNCA), navicular height, and calcaneal eversion distance[12–14] (Fig. 1). An orthopedic surgeon evaluated each radiograph to ensure that the specimens were neutrally aligned, that is, they had a neutral arch, a hindfoot absent of valgus or varus

Grant sponsor: Department of Veterans Affairs Rehabilitation Research and Development Service; Grant number: A4843C; Grant sponsor: University of Washington Medical Student Research Training Program.
Correspondence to: William R. Ledoux (T: +1-206-768-5347; F: +1-206-764-2127; E-mail: wrledoux@u.washington.edu)

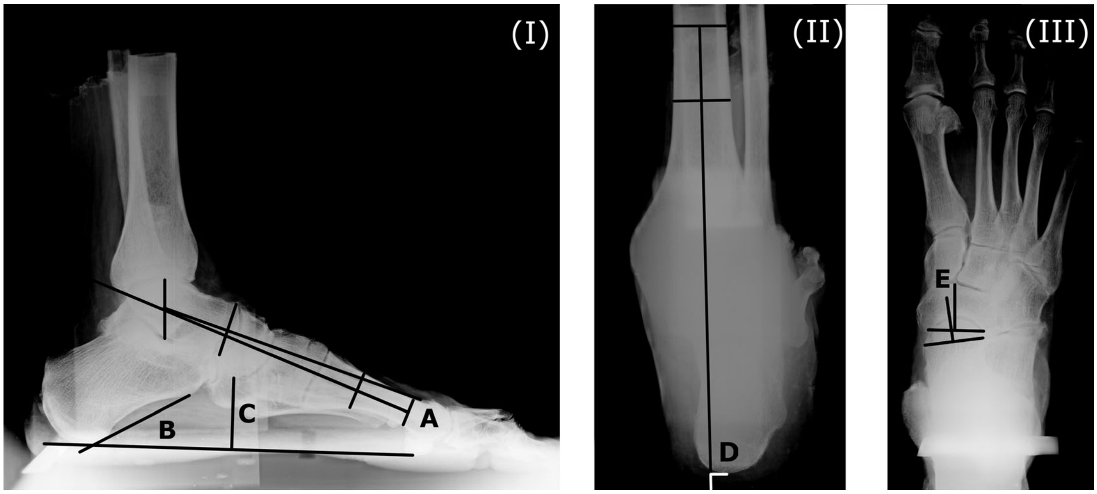

Figure 1. Radiograph of a neutrally aligned specimen including: (I) Medial/lateral [ML] radiograph with the (A) lateral talometatarsal angle [LTMA], (B) calcaneal pitch angle [CPA], and (C) navicular height [NH] measurements; (II) Hindfoot alignment view with the (D) calcaneal eversion distance [CED] measurement; (III) Anterior/posterior [AP] view with the (E) talonavicular coverage angle [TNCA] measurement.[12–14]

deformity, and a forefoot absent of ab- or adduction. All specimens with pathological abnormalities, such as hallux valgus, were excluded.

Ligamentous attenuation and cyclical loading were utilized to induce a flatfoot deformity consistent with Stage II PTTD. The talocalcaneal interosseous, plantar first metatarsocuneiform, plantar naviculocuneiform, and anterior tibiotalar part of the deltoid ligament were attenuated using several 1–2 cm incisions parallel to the ligamentous fibers.[1] Additionally, the spring ligament and talonavicular capsule were transected by cutting deep into the anteromedial aspect of the talonavicular joint space and continuing along the medial talar surface. The PTT itself was not attenuated in the initial flatfoot preparation process.

Each specimen was fitted with a custom tibia-mounting device consisting of a steel insert placed into the intramedullary canal of the tibia and held in place with an aluminum shell, a screw through the tibia and fibula, and PMMA. The tibia-mounting device was subsequently attached to an MTS Mini Bionix 858 testing machine. Each specimen was cycled from 10 N to the donor's body weight for 20,000–35,000 cycles at 2 Hz. To induce accentuated calcaneal eversion, a 40° heel wedge interacted with the medial portion of the hindfoot (a less severe lateral wedge acting plantarly did not promote eversion in our setup). After cycling, specimens were again radiographed to quantify the amount of change following the flattening procedure. Each foot was further dissected to isolate the extrinsic muscle tendons, including the tibialis anterior (TA), extensor digitorum longus (EDL), extensor hallucis longus (EHL), peroneus longus (PL), peroneus brevis (PB), tibialis posterior (TP), FDL, flexor hallucis longus (FHL), and the Achilles.

Each specimen was then mounted in the RGS (Fig. 2), a custom cadaveric loading device based on an R2000 parallel robot (Mikrolar, Inc; Hampton, NH).[15,16] The RGS moved a force plate in series with a pressure plate (i.e., the ground) with inverse motion with respect to the fixed tibia. Stance phase simulations were performed in 4.09 s. Tibia kinematics were prescribed from in vivo data from 10 symptomatic pes planus subjects.[17] To simulate a near-physiologic ground reaction force (GRF), biomechanically realistic muscle forces

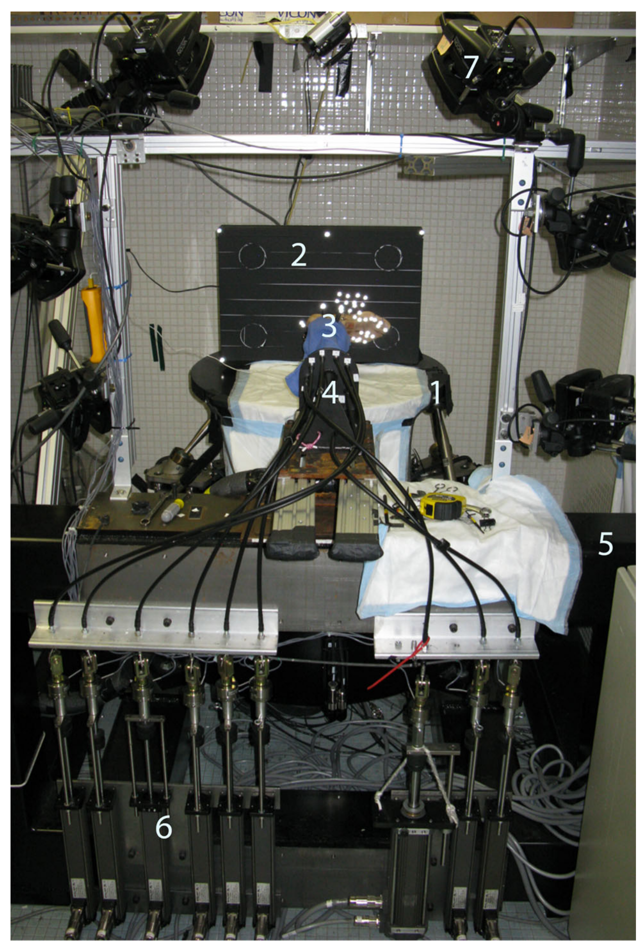

Figure 2. Robotic gait simulator (RGS) with mounted specimen. 1 = the R2000, 2 = force plate, 3 = cadaveric foot, 4 = tibial mount, 5 = loading frame, 6 = tendon actuators, and 7 = motion capture system.

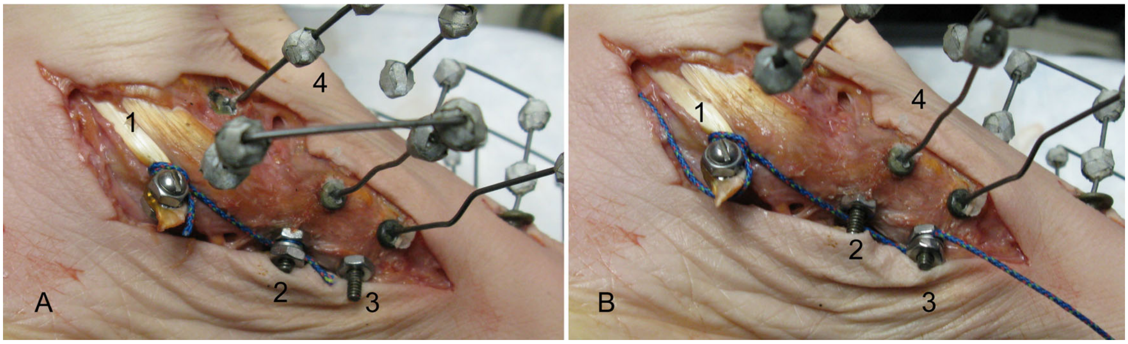

Figure 3. Transected flexor digitorum longus (FDL) tendon with custom fixation (via tendon clamp, string and hanger bolt) to the (A) navicular (NAV) and (B) medial cuneiform (CUN). 1 = FDL tendon with nylon string and bolt, 2 = hanger bolt attached to NAV, 3 = hanger bolt attached to CUN, and 4 = kinematic markers attached to the talus, NAV, and CUN.

determined from the literature were applied to the nine extrinsic muscle tendons via aluminum or plastic tendon clamps and linear actuators (except for the TP, which to simulate pathology, had no force applied). The RGS used three fuzzy logic controllers to achieve the target GRF, which, along with the muscle forces, were scaled to 50% of the donor's body weight to avoid breaking the often frail cadaver bones or avulsing tendons. The controllers adjusted the force applied by the TA and the Achilles tendon, as well as the position of the force plate normal to the foot, to achieve the target GRF; additionally, the controllers required three learning trials prior to each data trial, with three separate data trials being collected for each surgical condition.

Peak plantar pressure under the foot was measured with a novel emed-sf pressure platform attached to the surface of the force plate. An AP radiograph was used to apply a mask to the data to isolate the heel, medial midfoot, lateral midfoot, first through fifth metatarsals, hallux, and lesser toes. CoP data were normalized to foot length and width, and medial–lateral CoP position and range were analyzed using a method similar to De Cock et al.[18] The kinematics of individual foot bones were measured using a 6-camera Vicon system and a previously described 10-segment foot model.[16] Primary kinematic data were range of motion (ROM) and maximum angle during stance phase in all three cardinal planes for the talonavicular and the naviculocuneiform joints.

Each specimen was tested on the RGS under 4 conditions: flatfoot (FF), and then in randomized order, FDLTT to navicular (NAV; Fig. 3A), FDLTT to medial cuneiform (CUN) (Fig. 3B), and FDLTT to the residuum of PTT (rPTT). The flatfoot condition was tested first to record a baseline set of values. All applied muscle forces were set to their normal physiological level except for the PTT, which was set to zero to simulate degeneration of the tendon.

For both the NAV and CUN procedures, the FDL tendon was transected as far distal as possible without disrupting the plantar surface. Nylon string was clove-hitched to the distal FDL tendon, with a bolt and external tooth lockwasher inserted through the tendon acting as a stopper. The string was attached to the inferomedial aspect of either the navicular or medial cuneiform (NAV or CUN, respectively) by compressing it between two nuts on a hanger bolt drilled into the bone and reinforced with PMMA if necessary (Fig. 3). The string was positioned to produce a near-physiologic direction of pull on the navicular tuberosity or the inferomedial medial cuneiform. This method of tendon transfer was chosen over more clinically applicable methods (such as tenodesis or suture anchor) because of its transferability between sites while the specimen was mounted on the RGS. Moreover, we could simulate multiple surgical procedures without damaging the FDL tendon. For the NAV and CUN procedures, PTT force was zero, while 1.8× normal FDL force was used to simulate hypertrophy of the FDL in response to posterior tibialis atrophy after surgery.[19] The 1.8× factor was based on physiologic hypertrophy of 1.44× (a normal TP level) with an added safety factor of 25%. For the rPTT procedure, 1.8× normal FDL forces were applied to the PTT tendon, while the transected FDL forces were zero. For all three surgical models, all other applied muscles forces were modeled as in a normal foot. For kinematic and kinetic data, 84 trials were analyzed, including 7 feet with 12 trials each (3 each of FF, CUN, NAV, and rPTT).

Linear mixed effects regression was used to determine if biomechanical parameters changed after surgery. The parameter was the dependent variable, surgery type was

Table 1. Mean [SE] Pre-Surgery Radiographic Measures and Mean Differences From Pre-Flattened to Post-Flattened

	Pre-Flattened Procedure	Change From Pre- to Post-Flattened Procedure	p-Value (Paired t-Test)
Calcaneal pitch angle (°)	24.4 [1.3]	−1.3 [0.8][a]	0.17
Lateral talometatarsal angle (°)	−1.7 [2.2]	10.8 [0.9][b]	<0.001*
Navicular height (mm)	35.2 [1.9]	−8.1 [1.2]	<0.001*
Talonavicular coverage angle (°)	23.5 [1.9]	7.8 [2.8][c]	0.036*
Calcaneal eversion distance (mm)	7.7 [1.8]	7.4 [2.0]	0.011*

[a]negative = calcaneal plantar flexion. [b]positive = first metatarsal dorsiflexion. [c]positive = navicular abduction. *Significant difference between pre-flattening and post-flattening.

modeled as the independent fixed effect, and specimen and the specimen-condition interaction were modeled as random. Significance was set at $p = 0.05$ and determined using the likelihood ratio test. If a significant association was found between biomechanical parameter and surgery type, pairwise differences among surgery type and pre-surgery FF condition were assessed using Bonferroni's correction for multiple comparisons ($p = 0.05/6 = 0.0083$). Analyses were conducted using R 2.14.0[20] and the lme4 package.[21]

RESULTS

The mean changes in radiographic parameters from the attenuation and cycling procedures were consistent with flatfoot deformity (Table 1). The first metatarsals dorsiflexed relative to the tali ($p < 0.001$), the height of the navicular decreased ($p < 0.001$), the navicular abducted relative to the talus ($p = 0.036$), and the calcanei everted ($p = 0.011$).

For the 84 trials measuring kinematic and kinetic data, the RGS accurately generated the vertical GRF, with the root mean square (RMS) error from the target in vivo data averaging 4.8% body weight across all trials (Fig. 4). Since anterior/posterior and medial/lateral GRF were not controlled, they deviated more from the target, with RMS errors of 12.9% and 6.7% body weight, respectively (Fig. 4). The in vivo tibia with respect to ground kinematics in all planes closely matched the prescribed fixed angles to within ± 1 SD of the in vivo data for all but the final 10% of stance phase (Fig. 5). The average RMS tracking error for the EHL, EDL, FHL, FDL, PB, and PL tendons was 2.7 N across all 84 trials (data not shown). The RMS tracking errors for the Achilles and TA tendon forces were not calculated because the target tendon force was specified in real time by the fuzzy logic vertical GRF controller.

Peak plantar pressure generally decreased on the medial side after the FDLTT procedures (Table 2). Significant decreases in pressure occurred from the flatfoot conditions for the hallux with the CUN procedure ($p < 0.0083$), and for the first metatarsal with the NAV procedure ($p < 0.0083$). General, non-significant trends ($p > 0.0083$) suggested that the rPTT procedure yielded the greatest increase in pressure at the second metatarsal, but no other significant differences between surgical transfer sites were observed.

Mean CoP maximum, minimum, and range in the medial–lateral direction showed no significant differences between flatfoot and any surgery type (Table 3). Decreasing trends in CoP maximum (CUN and rPTT procedures) and minimum (all three procedures) indicated a non-significant medial shift in the CoP (Fig. 6). CoP range showed minimal change from the flatfoot condition. There were no significant differences between surgical transfer sites.

Kinematic data yielded a single significant difference between flatfoot and transfer simulations (Table 4). An increase in the max dorsiflexion of the medial cuneiform with respect to the navicular occurred from flatfoot to the NAV procedure ($p < 0.0083$). This is somewhat counter intuitive, and with only 1.0° of change, does not provide strong evidence to a reduction of flatfoot. No significant differences between surgical transfer sites were observed.

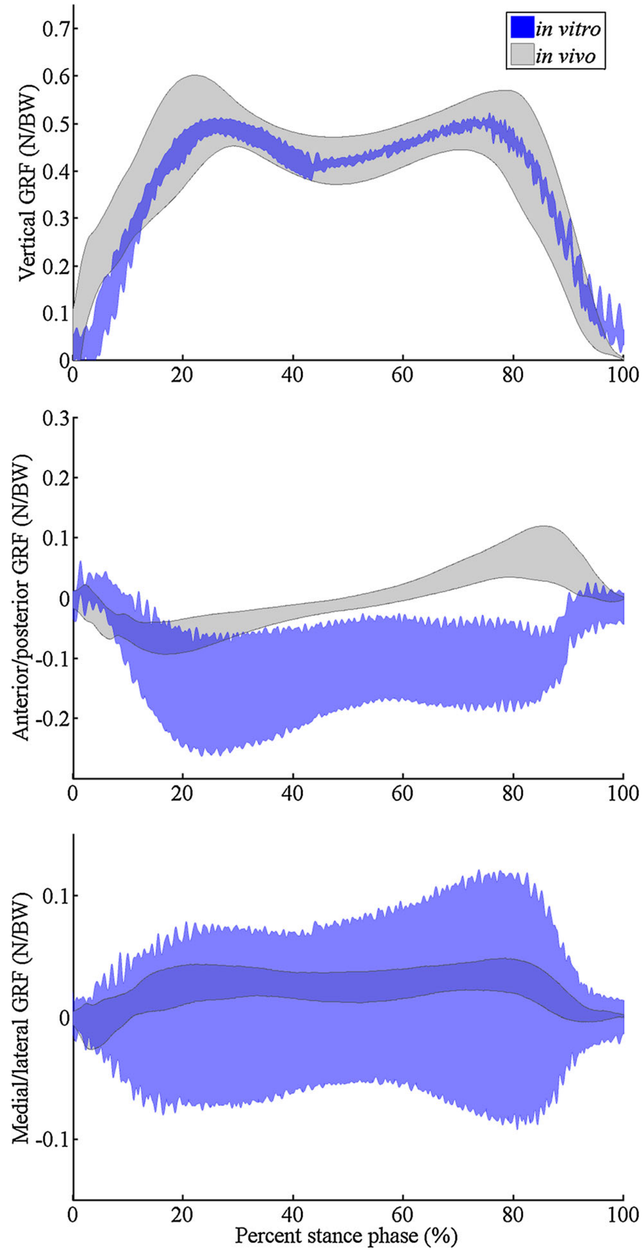

Figure 4. Mean $\pm$ 1 SD in vitro ground reaction forces (blue) for all 7 feet with 12 trials/foot (3 each of FF, CUN, NAV, and rPTT) compared to target mean $\pm$ 1 SD in vivo flatfoot ground reaction forces (gray). FF, flatfoot; CUN, cuneiform attachment; NAV, navicular attachment; rPTT, residuum of posterior tibial tendon attachment.

DISCUSSION

Our goal was to ascertain the relative differences in plantar pressure distribution and bony kinematics between flattened and surgically corrected specimens that have undergone an FDLTT as a proxy for clinical improvement. In performing a flattening procedure to simulate Stage II PTTD, followed by dynamic stance

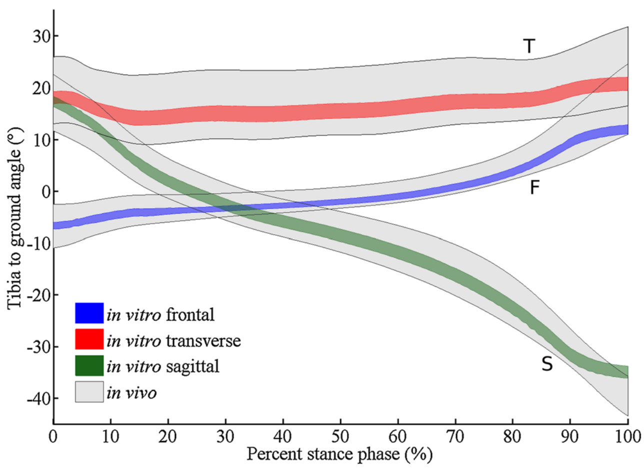

Figure 5. Mean in vitro ±1 SD tibial angles for the frontal (blue), transverse (red), and sagittal (green) planes for all 7 feet with 12 trials/foot (3 each of FF, CUN, NAV, and rPTT) compared to mean ± 1 SD flatfoot in vivo tibia with respect to ground fixed angles (gray). F, frontal plane; T, transverse plane; S, sagittal plane. FF, flatfoot; CUN, cuneiform attachment; NAV, navicular attachment; rPTT, residuum of posterior tibial tendon attachment.

phase gait simulation and several iterations of the FDLTT procedure, we aimed to better understand the effects of altering the attachment point of the tendon. Compared to the flatfoot condition, the three locations tested had minimal changes, with the NAV and CUN procedures having decreased medial pressures.

Analysis of the radiographic measurements showed significant changes towards the desired Stage II PTTD flatfoot in four of the five measures of interest. LTMA for adult acquired flatfoot has been measured to be ~20° [12,22,23]; the increase in LTMA from −1.7° to 9.1° (collapsing arch) in our study falls in the range indicative of Stage II flatfoot. Arangio et al. reported a normal TNCA of 21° [23], while flatfoot TNCA has been reported between 28.5°[22] and 36°.[23] The increase in TNCA from 23.5° to 31.3° (forefoot abduction) in our study shows an adequate model of flatfoot. Arangio et al.[23] reported a normal calcaneal eversion distance of 3 mm, with flatfoot ranging from 12 to 23 mm. The increase in calcaneal eversion distance from 7.7 to 15.1 mm (hindfoot valgus) falls well into the range of Stage II flatfoot. Lastly, the decrease of 8.1 mm in navicular height indicates a collapse of the medial arch of the foot. CPA, with an average angle of 23.1°, was the only metric that did not fall into a range consistent with flatfoot. Sangeorzan et al.[12] reported an average flatfoot CPA of 3.2° (calcaneal plantar flexion).

Peak plantar pressure analysis yielded significantly decreased medial pressures and trends for increased lateral pressures for the FDLTT procedures compared to the flatfoot condition, but no differences between FDLTT sites. Benthien et al. found that lateral pressures increased from 24.6 ± 9.0 kPa in the flatfoot condition to 33.9 ± 7.5 kPa after simulated FDLTT to the navicular and lateral column lengthening.[24] However, the inclusion of the lateral column lengthening procedure makes it difficult to discern the biomechanical effect of the FDLTT alone. Arangio et al.[25] reported that an FDLTT to the navicular decreased the talonavicular joint load by only a fraction of that accomplished by a concomitant MCO. While it appears that the FDLTT may have a diminished impact on reducing

Table 2. Mean [SE] for FF and Mean Difference [SE] From FF for Peak Plantar Pressure Regions

		Differences From FF (Surgery: FF; kPa)			
Biomechanical Measure	FF (kPa)	CUN	NAV	rPTT	p-Value[§]
Hallux	240 [39]	−31 [7]	−25 [8]	−24 [8]	0.0011[a]
First metatarsal	190 [29]	−8 [10]	−14 [4]	−13 [13]	0.0002[b]
Second metatarsal	205 [31]	3 [7]	9 [3]	13 [5]	0.067
Third metatarsal	165 [18]	10 [4]	17 [6]	5 [2]	0.034
Fourth metatarsal	102 [20]	15 [7]	10 [4]	0 [3]	0.12
Fifth metatarsal	62 [16]	20 [16]	12 [10]	8 [8]	0.55

FF, flatfoot; CUN, cuneiform attachment; NAV, navicular attachment; rPTT, residuum of posterior tibial tendon attachment.[§]Overall p-value.[a]Significant difference between FF and CUN, $p < 0.0083$.[b]Significant difference between FF and NAV, $p < 0.0083$.

Table 3. Mean [SE] for FF and Mean Difference [SE] From FF for Medial–Lateral Center of Pressure (CoP) Maximum (Max), Minimum (min) and Range

		Differences From FF (Surgery: FF)			
Biomechanical Measure	FF	CUN	NAV	rPTT	p-Value[§]
CoP max	0.084 [0.049]	−0.021 [0.013]	0.009 [0.010]	−0.019 [0.016]	0.27
CoP min	−0.15 [0.040]	−0.17 [0.040]	−0.15 [0.036]	−0.18 [0.034]	0.14
CoP range	0.23 [0.042]	−0.005 [0.011]	0.009 [0.006]	0.007 [0.008]	0.37

Values are normalized to foot length and width. For max and min, a negative value indicates a medial shift. FF, flatfoot; CUN, cuneiform attachment; NAV, navicular attachment; rPTT, residuum of posterior tibial tendon attachment.[§]Overall p-value.

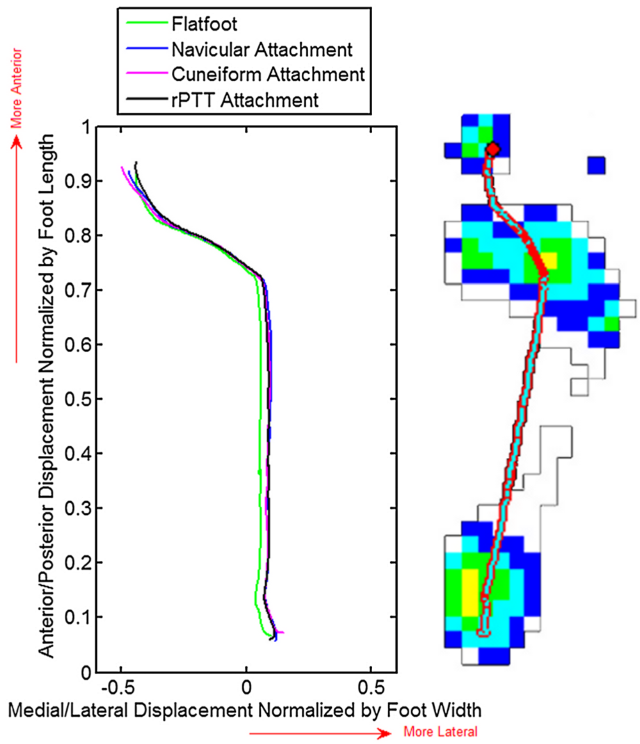

Figure 6. A representative CoP progression for the flatfoot and each of the soft tissue attachment points tested (three trials each) from one specimen. A raw pressure trace from a flatfoot trial is also shown for orientation.

medial plantar pressure and medial joint loads compared to a lateral bony realignment, our study also investigated pressure changes associated with isolated FDLTT to different locations.

CoP analysis did not show conclusive evidence of the correction of flatfoot, as the expected lateral shift was not seen. In fact, the FDLTT procedures appeared to slightly shift the CoP medially. No significant differences were noted amongst the 3 FDL transfer sites. Static gait studies conducted by Imhauser et al. similarly showed that in a cadaveric flatfoot model, loading of the PTT during stance phase was unable to move the CoP laterally.[26] It is likely that FDLTT alone will not result in large changes in the CoP.

The novel assessment from our study was the bony kinematics of cadaveric specimens with simulated Stage II PTTD before and after simulated FDLTT. Numerous studies looked at in vivo hindfoot kinematics in patients with PTTD,[27–29] and in general, small but significant changes in the hindfoot complex kinematics were observed. Niki et al.[5] tested cadaveric Stage II PTTD feet with and without the functionality of the PTT, and found that the PTT had little effect in overcoming the ligamentous laxity of the flatfoot model. Our results showed no significant kinematic differences between flatfoot and FDLTT conditions. Thus, an FDLTT alone may be insufficient to markedly alter bony kinematics in the Stage II PTTD model, at least without concomitant ligamentous tissue repair or bony procedure.

Our study had limitations. For instance, to simulate the flatfoot condition, we sectioned the spring ligament but did not repair it during FDLTT procedures. Clinically, the spring ligament is often repaired.[8,10] The tendon transfer procedure that we performed was easily accessible and transferable, but was not indicative of current practice, which would typically involve placing the FDL from plantar to dorsal through a navicular tunnel and suturing it back onto itself.[30] FDLTTs are not usually performed without a concomitant osseous procedure, such as an MCO. However, to simplify the study design and avoid additional variability due to an osseous procedure, we tested the FDLTT in isolation. Regarding kinematic and kinetic data, we generated the post-surgery cadaveric simula-

Table 4. Mean [SE] for FF and Mean Difference [SE] From FF of Three-Dimensional Joint Kinematics for the Talonavicular (nav_tal) and the Naviculocuneiform (nav_cun) Joints

		Differences From FF (Surgery: FF)			
Kinematic Measure (°)	FF	CUN	NAV	rPTT	p-Value[§]
nav_tal_c_rom	15.6 [1.3]	0.48 [0.17]	0.45 [0.17]	0.34 [0.20]	0.02
nav_tal_t_rom	12.8 [1.6]	−0.89 [0.58]	−0.20 [0.53]	0.12 [0.56]	0.14
nav_tal_s_rom	5.9 [1.3]	−1.00 [0.65]	−0.76 [0.84]	−1.00 [0.74]	0.21
nav_tal_c_max	26.4 [4.2]	−1.24 [0.90]	−0.91 [0.78]	−0.39 [0.49]	0.44
nav_tal_t_max	−9.7 [2.3]	−0.64 [1.05]	−0.30 [0.81]	−0.49 [0.44]	0.47
nav_tal_s_max	−17.1 [5.3]	−1.20 [0.75]	−1.04 [0.68]	−0.69 [0.55]	0.32
cun_nav_c_rom	7.4 [0.7]	−0.49 [0.40]	−0.67 [0.33]	−0.41 [0.28]	0.26
cun_nav_t_rom	4.3 [0.5]	−0.04 [0.24]	0.01 [0.47]	0.17 [0.17]	0.34
cun_nav_s_rom	9.0 [1.1]	−0.52 [0.30]	−0.24 [0.36]	0.16 [0.19]	0.36
cun_nav_c_max	2.1 [3.6]	0.43 [0.27]	0.17 [0.33]	−0.18 [0.28]	0.17
cun_nav_t_max	6.2 [3.3]	−0.36 [0.43]	−0.11 [0.52]	0.26 [0.14]	0.081
cun_nav_s_max	8.1 [7.0]	0.36 [0.21]	1.00 [0.25]	0.26 [0.19]	0.011[a]

FF, flatfoot; CUN, cuneiform attachment; NAV, navicular attachment; rPTT, residuum of posterior tibial tendon attachment; c, coronal plane; t, transverse plane; s, sagittal plane; ROM, range of motion. Kinematic measures read; for example, "range of motion of navicular with respect to talus in the coronal plane" (nav_tal_c_rom). For "max," an increase indicates eversion, abduction, and dorsiflexion.[§]Overall p-value.[a]Significant difference between FF and NAV, $p < 0.0083$.

tions with the same pre-surgery kinematic inputs; this assumption fails to account for changes in the GRF or muscle forces that would have occurred as a result of surgery. Subjects likely walk differently postoperatively. Also, the GRFs and target muscle forces were scaled to 50% body weight, with the simulations performed six times slower than in vivo stance phase; while this may lead to small kinematic and kinetic differences from in vivo, comparisons between surgeries in this study should not be affected. And as noted, the vertical GRF (which our controller tracked) was more accurate than the AP or medial/lateral GRF. Additionally, our study was performed on cadaveric specimens rather than living subjects, but that is modulated by the fact that this was a repeated measures analysis. A related consideration is that while absolute plantar pressures were on the order of magnitude experienced by living subjects, we were primarily interested in the relative differences between surgical conditions. Finally, loading the specimens to only 25% body weight when collecting radiographs may have masked more extreme bony changes.

Our purpose was not to determine if a concomitant calcaneal osteotomy needs to be performed with a FDLTT to treat Stage II PTTD. Our goal was to measure the relative effectiveness of each transfer location. We studied one procedure (rPTT) that simulated suturing the FDL tendon to the PTT, thus taking advantage of the natural PTT insertion, and two procedures that simulated direct transfer of the FDL to either the navicular or the medial cuneiform. Our conclusion was that the choice of transfer location for FDL is largely equivalent, as no differences were found between surgeries for any parameter. Additionally, the subtleties seem to confirm clinical practice in that the FDLTT alone (without a concomitant osseous procedure) is unlikely to correct the functional biomechanical deficits found in moderate adult onset flatfoot deformity, regardless of transfer location. In summary, the FDLTT procedures to the navicular and medial cuneiform significantly reduced pressure on the medial side of the foot, but no surgery altered the CoP, and there was a minimal change in the kinematics of the foot. Future studies should aim to determine the effects of FDLTT site in combination with an MCO.

ACKNOWLEDGMENTS

Jane B. Shofer, M.S. completed the statistical analysis. The funding sources played no role in this investigation.

REFERENCES

1. Blackman AJ, Blevins JJ, Sangeorzan BJ, et al. 2009. Cadaveric flatfoot model: ligament attenuation and Achilles tendon overpull. J Orthop Res 27:1547–1554.
2. Funk DA, Cass JR, Johnson KA. 1986. Acquired adult flat foot secondary to posterior tibial-tendon pathology. J Bone Joint Surg Am 68:95–102.
3. Kettelkamp DB, Alexander HH. 1969. Spontaneous rupture of the posterior tibial tendon. J Bone Joint Surg Am 51:759–764.
4. Myerson MS. 1996. Adult acquired flatfoot deformity: treatment of dysfunction of the posterior tibial tendon. J Bone Joint Surg 78-A:780–792.
5. Niki H, Ching RP, Kiser P, et al. 2001. The effect of posterior tibial tendon dysfunction on hindfoot kinematics. Foot Ankle Int 22:292–300.
6. Johnson KA, Strom DE. 1989. Tibialis posterior tendon dysfunction. Clin Orthop Relat Res 239:196–206.
7. Myerson MS. 1997. Adult acquired flatfoot deformity: treatment of dysfunction of the posterior tibial tendon. Instr Course Lect 46:393–405.
8. Sizensky JA, Marks RM. 2003. Medial-sided bony procedures: why, what, and how? Foot Ankle Clin 8:539–562.
9. Myerson MS, Badekas A, Schon LC. 2004. Treatment of stage II posterior tibial tendon deficiency with flexor digitorum longus tendon transfer and calcaneal osteotomy. Foot Ankle Int 25:445–450.
10. Neufeld SK, Myerson MS. 2001. Complications of surgical treatments for adult flatfoot deformities. Foot Ankle Clin 6:179–191.
11. Hui HE, Beals TC, Brown NA. 2007. Influence of tendon transfer site on moment arms of the flexor digitorum longus muscle. Foot Ankle Int 28:441–447.
12. Sangeorzan BJ, Mosca V, Hansen ST Jr. 1993. Effect of calcaneal lengthening on relationships among the hindfoot, midfoot, and forefoot. Foot Ankle 14:136–141.
13. Saltzman CL, el-Khoury GY. 1995. The hindfoot alignment view. Foot Ankle Int 16:572–576.
14. Williams DS, McClay IS. 2000. Measurements used to characterize the foot and the medial longitudinal arch: reliability and validity. Phys Ther 80:864–871.
15. Aubin PM, Whittaker EC, Ledoux WR. 2012. A robotic cadaveric gait simulator with fuzzy logic vertical ground reaction force control. IEEE Trans Robotics 28:246–255.
16. Whittaker EC, Aubin PM, Ledoux WR. 2011. Foot bone kinematics as measured in a cadaveric robotic gait simulator. Gait Posture 33:645–650.
17. Whittaker EC, Hahn ME, Rohr ES, et al. 2011. Foot bone motion in cavus, neutral and planus feet using an in vivo kinematic foot model. Gait Posture (in preparation).
18. De Cock A, Vanrenterghem J, Willems T, et al. 2008. The trajectory of the centre of pressure during barefoot running as a potential measure for foot function. Gait Posture 27:669–675.
19. Rosenfeld PF, Dick J, Saxby TS. 2005. The response of the flexor digitorum longus and posterior tibial muscles to tendon transfer and calcaneal osteotomy for stage II posterior tibial tendon dysfunction. Foot Ankle Int 26:671–674.
20. Team RDC. 2011. *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
21. Bates D, Maechler M, Bolker B. 2011. lme4: Linear mixed-effects models using S4 classes. R package version. R package version 0999375-42.
22. Ellis SJ, Deyer T, Williams BR, et al. 2010. Assessment of lateral hindfoot pain in acquired flatfoot deformity using weightbearing multiplanar imaging. Foot Ankle Int 31:361–371.
23. Arangio G, Rogman A, Reed JF III. 2009. Hindfoot alignment valgus moment arm increases in adult flatfoot with Achilles tendon contracture. Foot Ankle Int 30:1078–1082.
24. Benthien RA, Parks BG, Guyton GP, et al. 2007. Lateral column calcaneal lengthening, flexor digitorum longus transfer, and opening wedge medial cuneiform osteotomy for flexible flatfoot: a biomechanical study. Foot Ankle Int 28:70–77.

25. Arangio GA, Salathe EP. 2009. A biomechanical analysis of posterior tibial tendon dysfunction, medial displacement calcaneal osteotomy and flexor digitorum longus transfer in adult acquired flat foot. Clin Biomech (Bristol, Avon) 24:385–390.
26. Imhauser CW, Siegler S, Abidi NA, et al. 2004. The effect of posterior tibialis tendon dysfunction on the plantar pressure characteristics and the kinematics of the arch and the hindfoot. Clin Biomech (Bristol, Avon) 19:161–169.
27. Ness ME, Long J, Marks R, et al. 2008. Foot and ankle kinematics in patients with posterior tibial tendon dysfunction. Gait Posture 27:331–339.
28. Houck JR, Neville C, Tome J, et al. 2009. Foot kinematics during a bilateral heel rise test in participants with stage II posterior tibial tendon dysfunction. J Orthop Sports Phys Ther 39:593–603.
29. Brodsky JW, Charlick DA, Coleman SC, et al. 2009. Hindfoot motion following reconstruction for posterior tibial tendon dysfunction. Foot Ankle Int 30:613–618.
30. Sullivan RJ, Gladwell HA, Aronow MS, et al. 2006. An in vitro study comparing the use of suture anchors and drill hole fixation for flexor digitorum longus transfer to the navicular. Foot Ankle Int 27:363–366.

SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article at the publisher's web-site.