

Extensor Tendon Transfers for Treatment of Foot Drop in Charcot-Marie-Tooth Disease: A Biomechanical Evaluation

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Abstract

Background: In Charcot-Marie-Tooth (CMT) disease, selective weakness of the tibialis anterior muscle often leads to recruitment of the long toe extensors as secondary dorsiflexors, with subsequent clawing of the toes. Extensor hallucis longus (EHL) and extensor digitorum longus (EDL) tendon transfers offer the ability to augment ankle dorsiflexion and minimize claw toe deformity. The preferred site for tendon transfer remains unknown. Our goal was to quantify ankle dorsiflexion in the “intact” native tendon state, compared with tendon transfers to the metatarsal necks or the cuneiforms. We hypothesized that EHL and EDL transfers would improve ankle dorsiflexion as compared with the intact state and would produce similar motion when anchored at the metatarsal necks or cuneiforms.

Methods: Eight fresh-frozen cadaveric specimens transected at the midtibia were mounted into a specialized jig with the ankle held in 20 degrees of plantarflexion. The EHL and EDL tendons were isolated and connected to linear actuators with suture. Diodes secured on the first metatarsal, fifth metatarsal, and tibia provided optical data for tibiopedal position in 3 dimensions. After preloading, the tendons were tested at 25%, 50%, 75%, and 100% of maximal physiologic force for the EHL and EDL muscles, individually and combined.

Results: Transfers to metatarsal and cuneiform locations significantly improved ankle dorsiflexion compared with the intact state. No difference was observed between these transfer sites. Following transfer, only 25% of maximal force by combined EHL and EDL was required to achieve a neutral foot position.

Conclusion: Transfer of the long toe extensors, into either the metatarsals or cuneiforms, significantly increased dorsiflexion of the ankle.

Clinical Relevance: The transferred extensors can serve a primary role in treating foot drop in CMT disease, irrespective of the presence of clawed toes. This biomechanical study supports tendon transfers into the cuneiforms, which involves less time, fewer steps, and easier tendon balancing without compromising dorsiflexion power.

Keywords: Charcot-Marie-Tooth, extensor tendon transfer, Hibbs transfer, foot drop, claw toes

Introduction

Foot drop and claw toes are interrelated clinical manifestations common to patients with Charcot-Marie-Tooth (CMT) disease. Due to selective weakening of the tibialis anterior muscle, the extensor hallucis longus (EHL) and extensor digitorum longus (EDL) muscles are recruited as ankle dorsiflexors. The resultant overactivation of EHL and EDL causes hyperextension at the metatarsophalangeal (MTP) joints, that is, clawing of the toes.^{1,2,4,6,8,13,16}

There is no consensus for the best technique to improve ankle dorsiflexion strength in CMT patients. Surgical strategies include transfer of the posterior tibial tendon (PTT) to

the dorsal midfoot as a tri-tendon anastomosis, or directly secured into one of the cuneiforms.^{11,15} Alternatively, transfer of the EHL and EDL tendons into the midfoot or forefoot can be performed. Assuming the EDL and EHL remain relatively unaffected by the peripheral neuropathy, they

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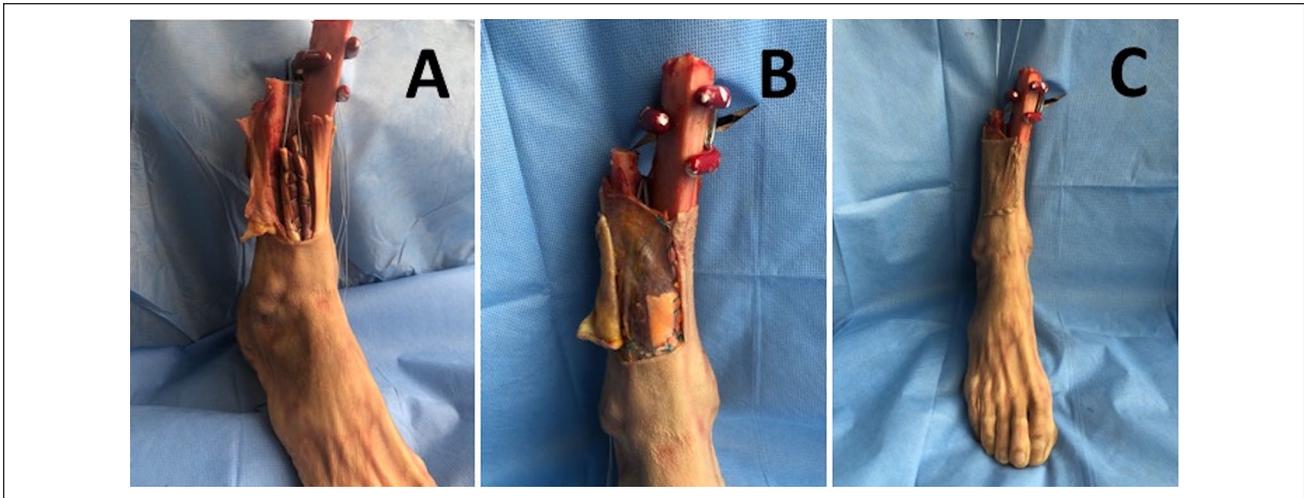


Figure 1. Specimen preparation. (A) Isolation of the extensor tendons within the anterior compartment with a looped suture. (B) Closure of the overlying anterior compartment fascia with a running Vicryl suture. (C) Closure of the skin with a running Monocryl suture to prevent tissue desiccation.

satisfy many theoretical principles of tendon transfer.²⁰ The long toe extensors are in phase with the tibialis anterior, have a direct line of pull, possess similar tendon excursions and power, perform a single function, and remain synergistic with each other. Furthermore, transfer of these tendons from the proximal phalanges eliminates the primary deforming force that causes clawing of the toes.

The best surgical transfer location of the EHL and EDL tendons is unknown. The initial description of transferring the EHL tendon into the metatarsal neck was presented by Jones⁷ in 1916 as a treatment for soldiers with claw foot. Transfer of the EDL tendons to the metatarsal necks was later reported by Hibbs⁵ in 1919 as a method to treat claw foot and restore ankle dorsiflexion power. Since these original descriptions, many modifications of the procedures have been proposed with alternative recipient sites in the midfoot, either secured into the cuneiforms or tenodesed to the tibialis anterior and peroneus tertius.^{1,6,8-10,14,16,17} There are currently no clinical or biomechanical studies evaluating the differences between transfer to the forefoot versus the midfoot. One study suggested that transfer to the metatarsal neck may provide an improved moment arm for dorsiflexion force generation at the ankle; however, no data were available to validate this claim.¹⁶

The primary objective of this study was to determine the amount of ankle dorsiflexion achieved when the EHL and EDL tendons are loaded in their native intact state, and compare it with transfers to the metatarsal necks or the cuneiforms. Our secondary objective was to analyze motion and alignment in the coronal and axial planes, between the intact state and each tendon transfer site. We hypothesized that EHL and EDL transfers would improve ankle dorsiflexion compared with the intact state by eliminating the energy

required to extend the MTP joints. Additionally, we hypothesized that tendon transfers to the metatarsals and cuneiforms would generate similar dorsiflexion due to the relatively rigid metatarsocuneiform joints. These data may help guide the surgical treatment of foot drop in CMT disease.

Methods

Specimen Preparation

Eight cadaveric foot and ankle specimens transected at midtibia and fibula (4 male, 4 female; average age, 47.4 ± 12.9 years) were obtained from an institution-approved tissue bank and stored at -30°C . Specimens were thawed at room temperature 24 hours in advance of testing. The specimens underwent fluoroscopic examination to ensure no degenerative changes or mechanical blocks to motion existed in the ankle or hindfoot, and a digital goniometer was used to document baseline range of motion (ROM) in plantarflexion and dorsiflexion. An L-shaped incision was made, extending distally along the tibial crest to 10 cm proximal to the ankle joint and exiting laterally toward the fibula. The anterior compartment fascia was opened, leaving a cuff along the tibial border for repair. The tibialis anterior, EHL, EDL, and peroneus tertius tendons were isolated in the leg. The EHL and EDL tendons were secured with a looped No. 2 braided polyblend suture (Fiberloop; Arthrex Inc, Naples, FL), leaving the loop intact for connection to linear actuators (Figure 1). The peroneus tertius was not included, as it could affect tendon dorsiflexion kinematics. The fascia and overlying skin were closed with a running suture to allow the tendons to glide in their native compartment and prevent desiccation during testing.

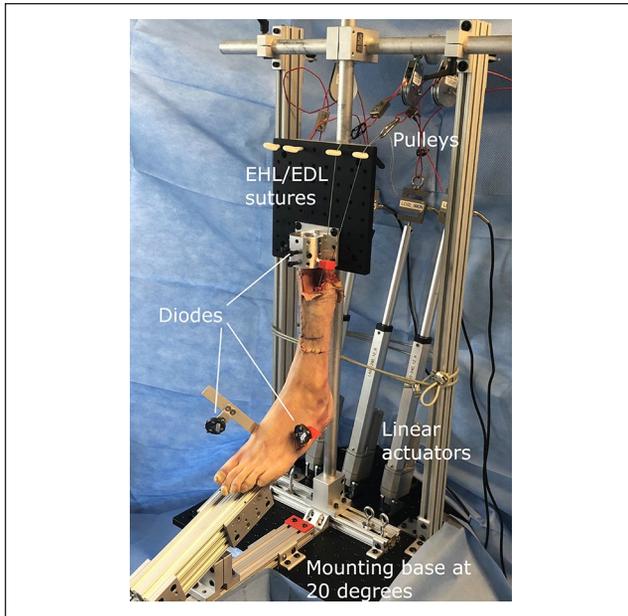


Figure 2. Specimen mounted into the custom testing apparatus with infrared diodes mounted to the first and fifth metatarsals and extensor tendon suture loops attached to the linear actuators via a pulley system. Oblique lateral view with labeled experimental components. EDL, extensor digitorum longus; EHL, extensor hallucis longus.

The specimen was mounted in a custom testing jig by clamping the tibia proximally with the ankle held at 20 degrees of plantarflexion. The extensor tendon suture loops were connected to linear actuators (FA-P0-240-12-8; Firgelli Automations, Ferndale, WA) via pulleys (Figure 2). The mounting base of the jig was retracted to the level of the metatarsals, to maintain 20 degrees of plantarflexion while minimizing constraint of the hindfoot during testing.

Longitudinal incisions were made along the medial and lateral borders of the first and fifth metatarsals, respectively, and infrared diodes were mounted directly to the metatarsals. A central diode was fixed to the proximal tibial clamp (Optotrak; Northern Digital Inc, Waterloo, ON, Canada). The anatomic ankle joint coordinate system was defined based on the long axis of the tibia and the transmalleolar axis, drawn between the centers of medial and lateral malleoli, to allow for kinematic analysis in 3 planes (Figure 3).²¹ Sagittal plane (tibiopedal plantarflexion or dorsiflexion) motion was measured by the first metatarsal diode position relative to the tibial axis, starting from a baseline 20-degree plantarflexed position. This initial tibiopedal angle was chosen in order to replicate the initial foot position in the swing phase of the gait cycle.³ Axial internal or external rotation of the foot was determined by the rotational change of the first metatarsal infrared diode relative to the transmalleolar

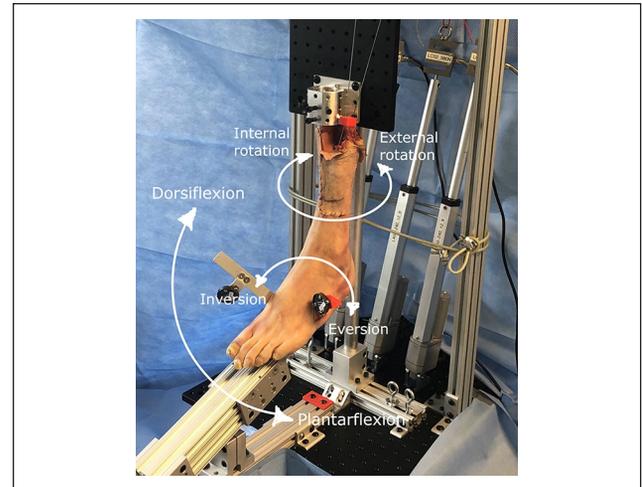


Figure 3. Planes of motion defined for the foot: sagittal plane dorsiflexion-plantarflexion, coronal plane eversion-inversion, and axial plane external rotation-internal rotation.

axis. In the coronal plane, inversion or eversion of the foot relative to the tibial axis was measured as the change in position of the fifth metatarsal relative to the first metatarsal.

Mechanical Testing

The EHL and EDL tendons were cyclically preloaded 5 times prior to testing each state. Maximum loads of 60 and 43 N were assigned for the EHL and EDL, respectively, based on the previously reported cross-sectional area and electromyographic force data of these muscles.¹² The EHL and EDL tendons were each individually loaded to 25%, 50%, 75%, and 100% of their maximum load, holding each force for 60 seconds, while new diode positions in the sagittal, axial, and coronal planes were recorded during the final 10 seconds of the loading. The EHL and EDL tendons were then simultaneously loaded to 25%, 50%, 75%, and 100% of their respective maximal loads (Figure 4). Each loading state was repeated 3 times and the averaged result was used for analysis.

Operative Techniques

Metatarsal Transfer. After testing each intact specimen, longitudinal incisions were made in the first and third web spaces at the level of the MTP joints. The EHL and EDL tendons to the second through fourth digits were transected at the distal aspect of the MTP joint. Each tendon was then sutured with 2-0 looped braided polyblend suture (Fiberloop; Arthrex Inc). The fifth ray EDL tendon was not transferred or tenotomized. Appropriately sized drill holes were made in metatarsals 1 to 4, just proximal to the articular margins. A Beath pin was used to pass the tendons

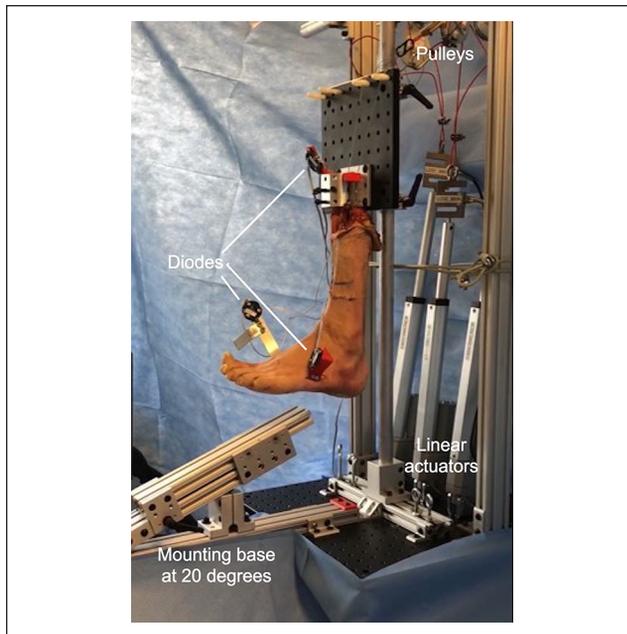


Figure 4. Intact state testing of extensor hallucis longus and extensor digitorum longus tendons with labeled components. Metatarsophalangeal hyperextension seen during intact state testing that mimics clinical claw toe pathology.

from dorsal to plantar. A 4.0×10 -mm biocomposite interference screw was inserted for fixation of the EHL, and 3.0×8.0 -mm biocomposite interference screws for the second through fourth metatarsals (AR-1540BC/AR-1530BC; Arthrex Inc) (Figure 5). Maintaining 20 degrees of plantarflexion, the looped sutures were grouped and tensioned in order to ensure a balanced transfer of all tendons. Metatarsal transfer state testing was repeated in the same fashion with 5 preloading cycles followed by experimental cycles.

Cuneiform Transfer. Fluoroscopy was used to localize the medial and lateral cuneiforms prior to creating longitudinal incisions over the midfoot. The EHL and EDL tendons were isolated at the level of the cuneiforms and transected 1 cm distal to the metatarsocuneiform joint. One No. 2 looped braided polyblend suture was used to hold the EHL, which was passed using a Beath pin into an appropriately sized drill hole in the center of the medial cuneiform, from dorsal to plantar. This procedure was repeated for the bulked EDL tendons into the lateral cuneiform. With the foot in 20 degrees of plantarflexion, the tendons were tensioned equally and fixed with either 4.75×15 -mm, 5.5×15 -mm, or 6.0×15 -mm biocomposite interference screws (AR-1547BC/AR-1555BC/AR-1560BC; Arthrex Inc) (Figure 6). Cuneiform transfer state testing was performed, as before, with 5 preloading and experimental cycles.

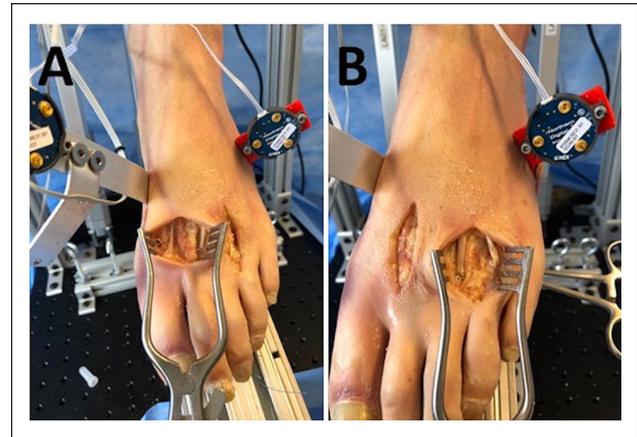


Figure 5. Forefoot extensor tendon transfers fixed with biocomposite interference screws. (A) EHL tendon transfer to the first metatarsal neck and second toe EDL tendon transfer to the second metatarsal neck performed through a single dorsal medial incision. (B) EDL tendon transfers to the third and fourth metatarsal necks performed through a single dorsal lateral incision. EDL, extensor digitorum longus; EHL, extensor hallucis longus.

Statistical Analysis

An a priori power analysis was calculated (G*Power 3.0.10) using previously reported means and standard deviations from a study on transmembranous PTT transfer.¹⁸ An effect size of 1.2 was determined and used to estimate that a minimum of 7 specimens would be required for 80% power with alpha set at 0.05. We performed statistical analysis using PRISM software (version 7.04; Graphpad Software Inc, San Diego, CA). Each dependent variable of sagittal (dorsiflexion or plantarflexion), coronal (eversion or inversion), and axial (external or internal rotation) plane position was analyzed and compared between each experimental state (intact, metatarsal, or cuneiform) using repeated measures analysis of variance for each tendon test (EHL, EDL, or EDL+EHL) for all muscle forces (25%, 50%, 75%, and 100%). The Tukey-Kramer method was used to adjust for multiple comparisons within each tendon test with significance set at $P < .05$.

Results

The average (SD) passive ankle ROM was 21.6 degrees dorsiflexion and 37.9 degrees plantarflexion. Data from all 8 specimens were included in the analysis.

Sagittal Plane Kinematics

Sagittal plane tibiopedal kinematic data are reported as positive (+) for dorsiflexion and negative (–) for plantarflexion. With simultaneous loading of the EHL and EDL (Figure 7A), intact specimens gained dorsiflexion for

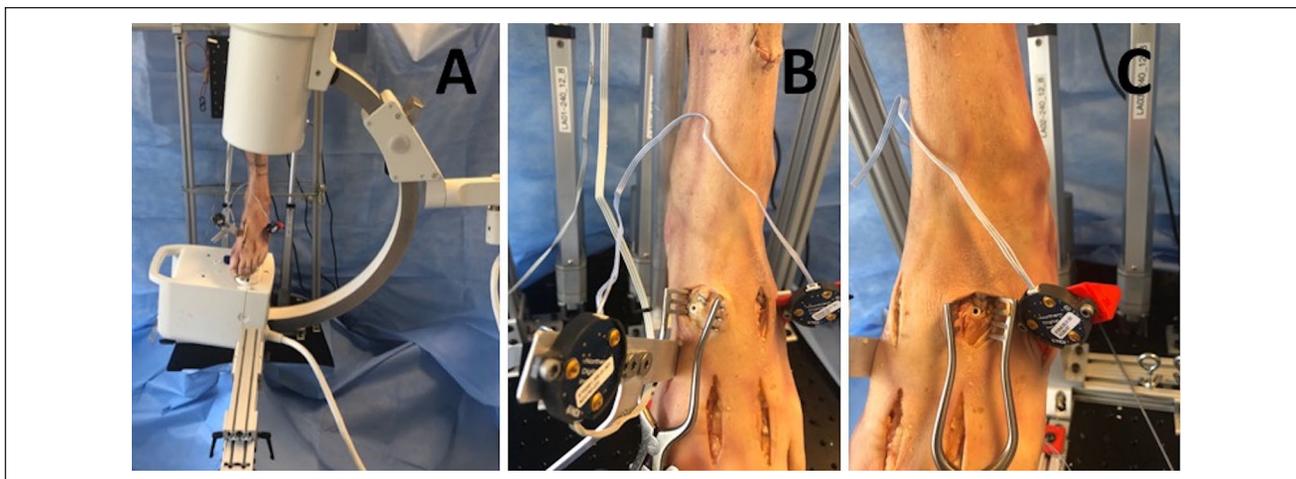


Figure 6. (A) Fluoroscopic localization of medial and lateral cuneiform tendon transfer sites. (B) EHL tendon transfer to the medial cuneiform. (C) Bundled EDL tendon transfer to the lateral cuneiform. EDL, extensor digitorum longus; EHL, extensor hallucis longus.

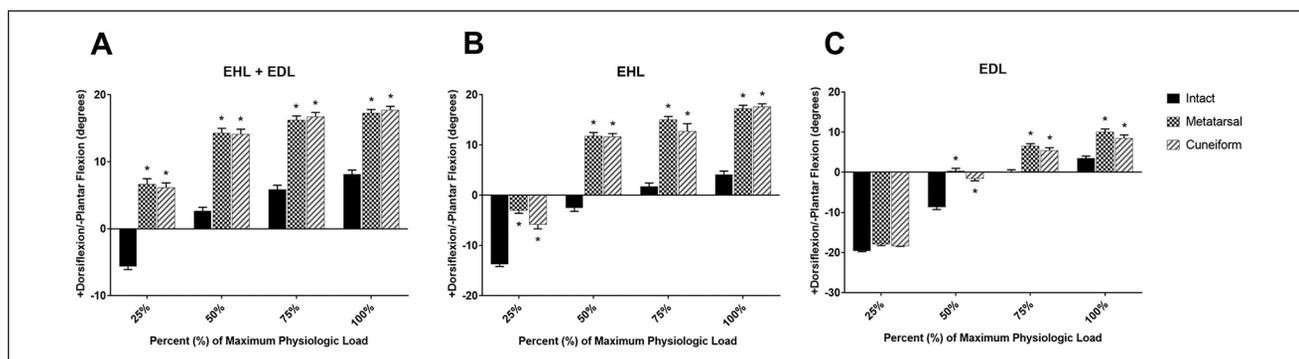


Figure 7. Average dorsiflexion achieved by each experimental state (intact, transfer to the metatarsals, or transfer to cuneiforms) under 25%, 50%, 75%, and 100% of physiologic muscle loads. Loading was performed for (A) combined EHL and EDL, (B) EHL only, and (C) EDL only. *Transfer states had significantly greater dorsiflexion at every percentage of muscle force compared with the intact state, $P < .01$. EDL, extensor digitorum longus; EHL, extensor hallucis longus.

each successive loading force, ultimately reaching $+5.9$ (± 1.8) degrees of dorsiflexion at peak loads. In comparison, both transfer states (metatarsals and cuneiforms) significantly increased dorsiflexion at each increment of loading force tested ($P < .01$). Even at 25% of the peak loads, both metatarsal and cuneiform transfer states exceeded 6 degrees of dorsiflexion.

When the EHL was loaded individually, the final position achieved by intact specimens averaged -13.7 , -2.5 , $+1.7$, and $+4.1$ degrees under 25%, 50%, 75%, and 100% of its maximal physiological load, respectively (Figure 7B). We observed greater dorsiflexion at every increment of muscle force tested for both transfer states ($P < .01$).

Likewise, when the EDL was loaded individually, the intact specimens gained increasing dorsiflexion, reaching a maximum of $+3.5$ (± 1.6) degrees at 100%. Transfer of the EDL to both the metatarsal necks and the cuneiforms

produced more dorsiflexion than the intact state at 50%, 75%, and 100% loads. The maximum dorsiflexion averaged $+10.1$ (± 2.1) and $+8.5$ (± 2.3) degrees, respectively (Figure 7C).

Whether the EDL and EHL tendons were loaded individually or simultaneously, there were no significant differences in ankle dorsiflexion between metatarsal or cuneiform transfer location at any load (Figure 7A–C).

Axial Plane Kinematics

Simultaneous loading of EHL and EDL tendons increased foot external rotation (+) relative to the tibial shaft axis for intact and transfer states with successive loading forces. Transfer to the metatarsal necks gained more external rotation than the intact state and cuneiform transfer state for all loads tested ($P < .01$) (Figure 8A). Loading the EDL

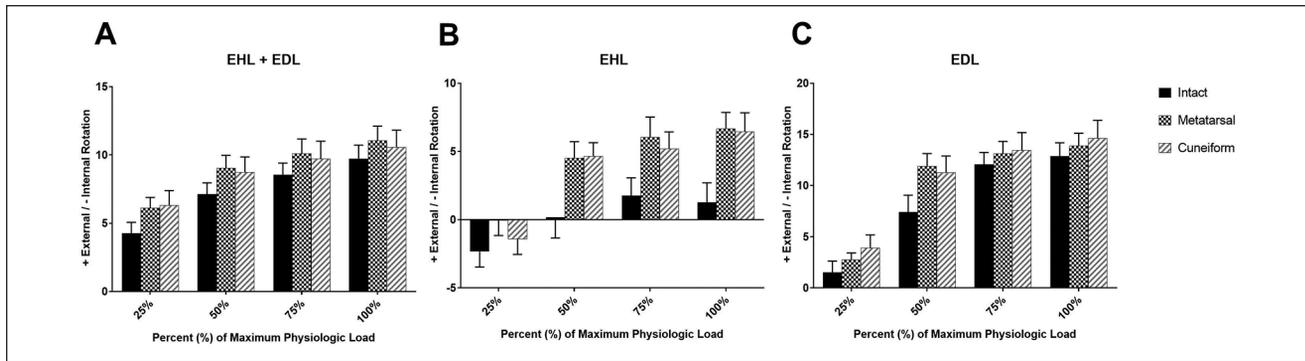


Figure 8. Average axial plane motion (+, external rotation; -, internal rotation) achieved by each experimental state (intact, transfer to the metatarsals, or transfer to cuneiforms) under 25%, 50%, 75%, and 100% of physiologic muscle loads. Loading was performed for (A) combined EHL and EDL, (B) EHL only, and (C) EDL only. EDL, extensor digitorum longus; EHL, extensor hallucis longus.

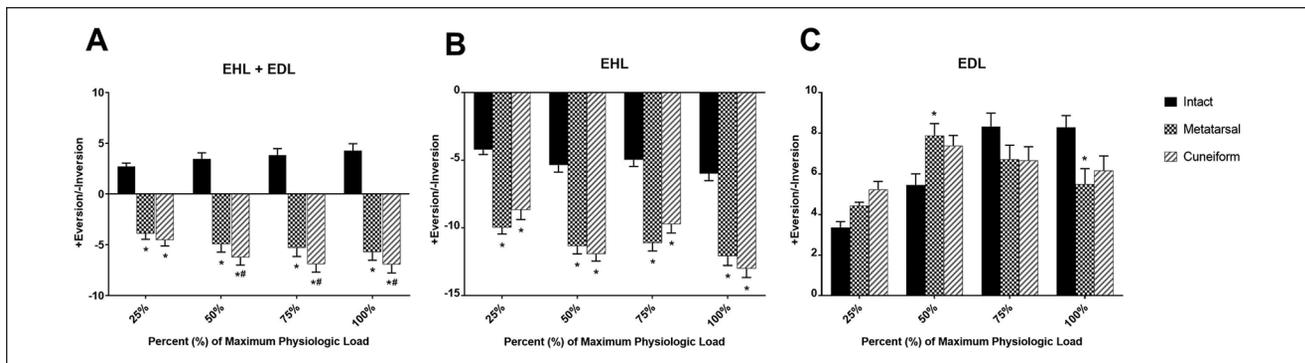


Figure 9. Average coronal plane motion (+, eversion; -, inversion) degrees achieved by each experimental state (intact, transfer to the metatarsals, or transfer to cuneiforms) under 25%, 50%, 75%, and 100% of physiologic muscle loads. *Significant difference compared with the intact state ($P < .001$). #Significant difference compared with the metatarsal state ($P < .05$). EDL, extensor digitorum longus; EHL, extensor hallucis longus.

individually (Figure 8C) produced greater external rotation compared with individual loading of the EHL (Figure 8B) for every testing state and muscle force evaluated.

Coronal Plane Kinematics

Isolated loading of the EHL produced inversion (-) of the foot relative to the neutral position, whereas isolated loading of the EDL resulted in eversion (+) for all testing states (Figure 9B,C). When the EHL and EDL tendons were simultaneously loaded in their intact state, the foot everted to $+4.3 \pm 2.0$ degrees at peak loads, respectively (Figure 9A). Following tendon transfer to the metatarsal necks, the final foot position was inverted $5.7 (\pm 2.3)$ degrees when both tendons were loaded to 100%.

Discussion

This study quantitatively compared native long toe extensor (EHL and EDL) tendon function with the effect of transfers

to the metatarsal necks and cuneiforms for the treatment of foot drop. Historically, the Hibbs and Jones transfers were described to address clawed toes, rather than aiding ankle dorsiflexion. The most significant finding of this study was that the tendon transfers, regardless of recipient location, significantly increased ankle dorsiflexion relative to the intact state. Furthermore, isolated function of either the transferred EHL or the transferred EDL could achieve greater dorsiflexion compared with the tendons in their native locations. CMT disease is characterized by a selective pattern of motor weakness that manifests as foot drop and compensatory toe clawing. Clinically, our biomechanical results suggest that toe extensor tendon transfers can have a primary role in augmenting dorsiflexion for CMT patients with symptomatic foot drop. This intervention also has the secondary advantage of minimizing claw toe deformity.

At all loads tested, transfer of the tendons to more proximal sites significantly improved dorsiflexion compared with the intact state. The longitudinal muscle pull was no longer expended as torque across the MTP joints, thereby

more efficiently driving ankle motion. This suggests that even in the presence of weakened long toe extensors, transfers may be beneficial. At 50% of maximal force, transfer of either the EHL or EDL tendons can generate enough force to dorsiflex the foot beyond neutral. Isolated transfer of a relatively strong EDL, therefore, would be beneficial to a CMT patient with a weak EHL. Following combined transfers, only a quarter of maximum physiologic muscle forces was required to eliminate foot drop. Although the amount of intrinsic and posttransfer weakness remains unknown in CMT patients, these results suggest that a proximal transfer, regardless of location, would have clinical benefit.

This study was the first to compare recipient sites of toe extensor transfers. We found no significant difference in the amount of dorsiflexion generated between transfer to the metatarsal necks and transfer to the cuneiforms when the EHL, EDL, or combined EHL and EDL was incrementally loaded. This may be attributable to minimal physiological motion across the medial tarsometatarsal joints.¹⁹ Thus, the location of transfer may be easily adjusted according to the concomitant procedures or by surgeon preference. There are risks such as iatrogenic fracture and unequal tensioning when transferring the extensors individually into the metatarsal necks. Transfers to the medial and lateral cuneiforms is an easier and less time-consuming alternative, with similar biomechanical outcomes.

The coronal and axial plane kinematic testing also provided useful clinical data. In the coronal plane, the native EDL and EHL tendons appear to balance excessive inversion and eversion. For both transfer states, the EHL overpowered the EDL and inverted the foot. This is likely a result of the higher load (60 vs 43 N) for the EHL simulated in the study and may not entirely reflect clinical kinematics. In the axial plane, the native EHL and EDL generated external rotation of the foot, relative to the baseline position. Transfer of the EHL and EDL tendons significantly increased forefoot external rotation relative to the intact state in most testing loads, when loaded both individually and together. This would be beneficial in many CMT patients who have weakened peroneus brevis function. Transfers involving the lateral cuneiform site might also facilitate unlocking of the transverse tarsal joints to generate a supple hindfoot prior to heel strike.

This study has several limitations inherent to those of cadaveric biomechanical investigations. One main unknown is the degree of motor weakness in the EDL and EHL muscles inherent in CMT patients, and the subsequent loss of power associated with transferring their tendons. The choice of 60 and 43 N for EHL and EDL strength was chosen based on the available literature but may not be applicable to the CMT population. Evaluating each transfer at 25%, 50%, 75%, and 100% of these “physiologic values” was aimed at eliminating this potential weakness. While it is often assumed that a muscle loses 1 motor grade following transfer, this may

not be true when the tendon is being transferred to a more proximal insertion site with the same line of pull. In any case, our findings suggest that the biomechanical advantage of the transfer can compensate for a potential motor loss. Another limitation is the use of interference screws for distal fixation in the metatarsal necks, which has only previously been described for the hallux EHL transfer. This was chosen to decrease differences in dorsiflexion strength based on tendon fixation technique. Use of a 3-mm anchor in the distal metatarsal did not have any observable slippage of the tendon throughout testing and was successfully performed in metatarsals 2 to 4 in all specimens without fracture of the metatarsal neck. Additionally, we were unable to randomize the order of the procedures, as testing the cuneiform transfer prior to metatarsal transfer would damage the tendons. Furthermore, intrinsic changes may occur over time with repetitive testing of the same tendon. The strength of this study is the ability to directly compare the procedures to each other in the same specimen, which may limit differences caused by anthropometric factors.

Conclusion

In conclusion, we believe the power of the long toe extensors has been underutilized in CMT surgery. These data demonstrate that their proximal transfer provides a significant biomechanical advantage for ankle dorsiflexion, achieving neutral dorsiflexion with only one-fourth of the typical muscle force. The present study also demonstrates that cuneiform transfers yield similar effects to metatarsal transfers, thereby supporting the use of midfoot recipient sites, which require less time and simplify tendon balancing without sacrificing dorsiflexion power. Thus, EHL and EDL transfers can be used not just for the treatment of claw toes, but also to significantly augment ankle dorsiflexion power in a CMT patient with drop foot.

Declaration of Conflicting Interests

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