The Normal and Pathologic Function of the Windlass Mechanism during Dorsiflexion of the Hallux

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INTRODUCTION: The windlass mechanism (WM) involves the plantar aponeurosis (PA) , which is a bundle of fibers that connects the calcaneus to the area near the base of the proximal phalanx [1]. Dorsiflexion of the first metatarsophalangeal joint (MTPJ1) (consisting of the first metatarsal and the first proximal phalanx) shortens the plantar portion of the foot, dorsiflexes the calcaneus, and raises the longitudinal arch. This increases the rigidity of the foot, allowing for push off, and it accumulates tension in the plantar tissue as if drawing a bow, providing propulsive force during walking [1]. Typically, the WM has been evaluated two-dimensionally, for instance, by measuring the height of the navicular in lateral plane radiographs [2]. Furthermore, the WM is involved in the pathogenesis of hallux valgus [3] and hallux rigidus [4]. However, since these foot conditions also include non-sagittal plane deformities, a three-dimensional analysis is ideal. The main functioning component of the WM, and the focus of this study, is the PA, [5]. While the Achilles tendon contributes to the dynamics of the WM, it is unclear how much of a role it plays. The purpose of this study was to analyze the WM three-dimensionally using cadaveric specimens representing normal and pathologic feet. We explored normal WM function, as well as how 1) an overpulled Achilles tendon and 2) a sectioned PA affected the WM. The hypothesis was that both an overpulled Achilles tendon and cut PA would decrease the navicular height and increase the medial longitudinal angle (MLA) compared to normal.

METHODS: Four fresh-frozen cadaveric foot specimens were transected approximately 12 cm proximal to the ankle joint. Specimens were screened for gross deformities and abnormal bony alignments at the first MTPJ1 (e.g., hallux valgus, claw toes) using preliminary fluoroscopy and CT scans. Normal foot alignments were confirmed by an orthopedic surgeon by reviewing the imaging data. Each of the nine extrinsic ankle tendons were then dissected. They were the Achilles, extensor digitorum longus, extensor hallucis longus, peroneal longus, peroneal brevis, tibialis posterior tendons, tibialis anterior, flexor digitorum longus, and flexor hallucis longus (FHL) tendons. Sutures were tied with a Krackow stitch to the proximal end of each tendon. The tibial and fibular shafts were denuded of tissues and solid polyester resin cylinders were cast around the bones to provide a uniform interface for a biomechanical testing frame that was used previously by our group [6]. The frame functioned to stabilize the specimen in a single pose through the duration of the scan; loads could be applied to the tibial shaft and the extrinsic musculature, while the foot underwent heel lift or toe rise. Only toe rise data were included in this abstract.

Each specimen was placed in the loading frame and static loads equivalent to 20% body weight were applied to the tibia shaft, with nominal loads applied to the extrinsic tendons. The MTPJ1 was then extended by adjusting a platform (Figure 1). The device was made without metal to reduce artifacts and used a rotary encoder to calculate the angle of the first proximal phalanx. Each specimen was scanned in seven configurations (first proximal phalanx angles 0-60°, each 10° apart) and three conditions (intact, Achilles overpull, and PA cut) using a pedCAT cone-beam CT (CBCT) scanner (voxel size = 0.3 mm isotropic). First, the foot was scanned with normal loads, and then excessive tension (225N) on the Achilles tendon, and finally with the PA was cut at the attachment to the calcaneus. The foot bones were segmented from the CBCT scan volumes in Mimics Research software v23.0 (Materialise N.V., Leuven, Belgium) in the neutral position under normal loading. Bone kinematics between the 20 subsequent scans were determined via volumetric image registration in custom MATLAB software for each segmented bone [6]. After that, we calculated the height of the navicular and the MLA in a 3D model using some additional custom MATLAB code. The height of the navicular was measured as the distance from the ground to the geometric center point. In the MLA, the angle was formed using three points: the farthest point of the first metatarsal head, the medial process of the calcaneus, and the apex being the navicular tuberosity. Means and standard deviations (mean ± SDs) were calculated and paired Student *t* tests was performed to analyze the difference between the three groups, with statistical significance set at $p < .05$.

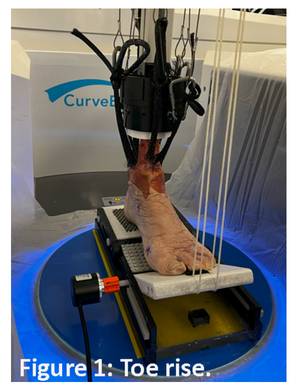

Figure 1: Toe rise.

Currently, the results are based on four feet, but we have a total of ten feet that have been tested and are currently being analyzed. The choice of 10 cadavers is arbitrary, but based on previous cadaveric studies. The data from this study will be used in power calculations for future larger studies conducted on our robotic gait simulator. Future work will include a full three dimensional analysis.

RESULTS: In all three conditions, navicular height increased and MLA decreased with dorsiflexion of the first proximal phalanx. In the overpulled Achilles tendon condition, the navicular height tended to decrease at the 30° (104.7 ±8.3 mm, p=0.03) and 40° (106.5 ±8.1 mm, p=0.04) first proximal phalanx angles compared to normal (109.1 ±6.7 mm, 110.7 ±7.9 mm), and there was no relation between navicular height and MLA for the two groups. In the PA cut condition, navicular height tended to decrease at the first proximal phalanx angles from 0° to 40° (99.6 ±6.0 mm, 98.5 ±5.6 mm, 100.3±5.9 mm, 101.8±5.7 mm, 103.4±5.9 mm. p=0.01, 0.04, 0.02, 0.03, 0.05), while MLA height tended to increase at proximal phalanx angles of 10° (139.1 ±5.4°, p=0.02) and 20° (135.7 ±3.8°, p=0.01).

DISCUSSION: In this study, a three-dimensional model was used to accurately measure the effect of WM. Although we only currently have a few cases analyzed, we found our methodology to be reliable and our hypothesis confirmed by the trends showing that pathological conditions diminished the function of the WM. The WM still worked even when the PA was cut. This indicates the WM is affected by not only the PA, but likely the FHL, flexor hallucis brevis, and other factors. As with any cadaveric study, there was a possibility that the dynamics of the cadaver differs from that of a healthy human foot. However, it was impossible to perform this study on living subjects due to the invasive nature of the testing, and the use of fresh-frozen cadavers was likely to yield new findings in this study.

SIGNIFICANCE/CLINICAL RELEVANCE: The present study provides basic data for researching the pathogenesis of diseases related to the WM.

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