

The Intact and Pathologic Function of the Windlass Mechanism during Extension of the Hallux

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INTRODUCTION: Normal foot function includes a biomechanical system known as the windlass mechanism (WM), which is thought to be activated during first metatarsophalangeal joint (MTPJ1) extension through tensioning of the plantar aponeurosis (PA) [1]. This action elevates the medial longitudinal arch (MLA) and contributes to effective propulsion during walking. While the WM is essential for normal gait mechanics, its behavior under pathological conditions is not fully understood. Moreover, the WM can be engaged with the foot on the ground and the MTPJ1 extended (i.e., toe rise) or with the toes on the ground and the heel off the ground (i.e., heel rise, which occurs in the late stance phase during gait). The PA, along with structures such as the Achilles tendon, flexor hallucis longus (FHL), and flexor hallucis brevis (FHB), is thought to stabilize the arch and coordinate foot motion. However, the extent to which each of these structures contributes to the WM has not been clearly defined. This study was designed to investigate how the WM functions when one or more of these structures are altered. We hypothesized that under such conditions as PA transection, FHB transection, and Achilles overpull—the WM would be less effective, resulting in reduced navicular height elevation and diminished joint motion during toe extension compared to normal, while for FHL overpull, the WM would be more effective than normal. To test this hypothesis, we performed three-dimensional, weightbearing computed tomography (CT) scans to measure foot and joint kinematics during toe rise and heel rise under intact and altered conditions. Unlike previous approaches based on anatomy, modeling, or motion capture, CT imaging enables direct observation of internal foot structures under physiological load. The objective was to quantify the biomechanical contributions of the PA, Achilles tendon, FHL, and FHB to the WM, and to clarify how its function is disrupted in pathological states.

METHODS: Ten fresh-frozen cadaveric lower limbs (4 pairs, 7M/3F, 6L/4R, 67.6 ± 10.0 years, 26.9 ± 3.9 BMI) were transected 12 cm proximally to the ankle. Each specimen was screened radiographically and physically by an orthopaedic surgeon to exclude abnormalities. Nine extrinsic tendons (Achilles, FHL, flexor digitorum longus (FDL), extensor digitorum longus (EDL), extensor hallucis longus (EHL), peroneus brevis (PB), peroneus longus (PL), tibialis anterior (TA), and tibialis posterior (TP)) were exposed and sutured with a Krackow stitch to fiber sheath to allow for controlled loading. Specimens were mounted in a custom loading frame and statically loaded with force tibial and muscle force equivalent to 20% body weight [2]. Two experimental configurations were tested: Toe rise, where MTPJ1 was extended using an adjustable platform, and heel rise, where MTPJ1 extension occurred through Achilles-driven ankle plantarflexion. For both configurations, seven target toe extension angles (0 to 60 degrees) were tested under five conditions: intact, Achilles overpull, FHL overpull, PA cut, and FHB cut. For each specimen (n=10) cone-beam CT scans (LineUp, voxel size 0.3 mm³) were obtained at each position (n=14) and condition (n=5). Bone segmentation (tibia, calcaneus, talus, navicular, medial cuneiform, first metatarsal, and proximal phalanx) was performed using Mimics in the 0 degree toe rise data. The bone-to-bone positions were obtained across 70 scans per specimen were quantified via customized volumetric image registration software (SCULPTOR) in MATLAB. Embedded coordinate systems were used to describe anatomical positions for the MTPJ1, talonavicular, cuneonavicular, and the medial cuneiform/first metatarsal (the tarsometatarsal joint or TMT). Navicular height was defined as the vertical distance from the ground to the geometric center of the navicular. Medial longitudinal arch (MLA) angle was defined using three anatomical landmarks: first metatarsal head, calcaneal medial process, and navicular tuberosity. The relationship between the actual (not target) MTPJ1 angle and each outcome (navicular height and MLA angle, as well as talonavicular, cuneonavicular, and TMT angle) was analyzed using linear mixed models. To capture potential non-linear effects, quadratic terms with condition-specific coefficients were included. Partial F-tests were used to test associations between MTPJ1 angle and each outcome and to determine whether these associations differed by condition. For this abstract, only navicular height is reported.

RESULTS: Navicular height changed systematically with hallux extension under both configurations (Figure 1). In toe rise, navicular height increased from 48.2 ± 1.7 mm at 0 degrees to 54.3 ± 1.6 mm at 60 degrees. Compared to normal, the Achilles overpull condition significantly reduced this elevation (p = 0.03), whereas FHL overpull (p = 0.72), PA cut (p = 0.11), and FHB cut (p = 0.55) showed no significant differences. However, in heel rise, navicular height decreased from 52.4 ± 2.1 mm at 0 degrees to 47.3 ± 2.1 mm at 60 degrees. Both Achilles overpull (p < 0.01) and FHL overpull (p < 0.01) significantly altered this relationship, whereas PA cut (p = 0.53) and FHB cut (p = 0.31) did not differ from intact.

DISCUSSION: This study demonstrated that the WM, assessed via navicular height and associated joint kinematics (data not shown), was most strongly influenced by excessive Achilles tendon tension. Although the PA is traditionally regarded as central to the WM function, transection of the PA did not significantly impair arch elevation in either configuration. Contrary to our initial hypothesis, this suggests that passive intrinsic plantar muscle also play a critical role in sustaining the WM; this is supported by the use of cadaveric specimens without active muscle contraction. Differences between toe rise and heel rise configurations were also observed. Toe rise produced a linear increase in navicular height with hallux extension, whereas heel rise exhibited a curvilinear pattern that initially decreased and before increasing at higher angles. This indicates that the WM functions differently in toe rise vs heel rise, with the former being representative of function during gait. In healthy individuals (with and without flat feet), navicular height has been reported to initially decrease and then increase during hallux extension, generating a characteristic curvilinear trajectory [3,4]. The heel rise condition from our data reproduced this pattern, indicating that despite the cadaveric model, our experimental setup successfully recreated a physiological representation of WM function during gait.

SIGNIFICANCE/CLINICAL RELEVANCE: These findings highlight that the WM is not solely dependent on the PA but is strongly influenced by Achilles tendon tension and likely supported by intrinsic plantar muscles. Understanding these contributions may help guide surgical decision-making and rehabilitation strategies aimed at preserving medial arch function.

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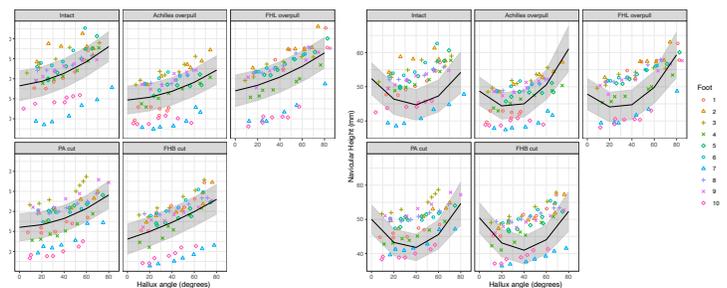


Figure 1: Navicular height: toe rise (left) and heel rise (right) for each condition.