

Passive Hindfoot Kinematics Within A Robot-Driven Tibial Sagittal Movement Envelope

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INTRODUCTION: Accurate description of bony motion can help us understand how individual joints in the foot and ankle compensate and interact with each other with injury, surgical intervention, or abnormality. Common *in vivo* foot models with skin-mounted retroreflective markers consolidate or ignore movement of the other bones and assume that the tibiotalar joint contributes to most of the foot and ankles mobility in the sagittal plane [1-3]. Recent work highlights significant individual movement of the tarsal and midtarsal bones, such as the talus, navicular, cuboid, and cuneiform, in normal feet [4]. Cadaveric models allow for invasive access to accurately measure individual bone motions and robotic systems can be used to simulate motions in cadavers [5]. While the focus on simulating gait in cadavers has allowed us to make many kinematic interpretations about dynamic foot and ankle bone motion, there have been limited efforts in quantifying the passive adaptability of the foot and ankle to perturbations. Therefore, the purpose of this study was to describe the passive joint kinematics of the hindfoot during range of motion testing with various forefoot and ankle perturbations using cadaveric robotic simulation.

METHODS: Five fresh-frozen tibia-to-toe tip cadaveric specimens (5 males; 53 ± 13 yrs old) with no history of foot and ankle injury or surgery were procured under University of Utah Institutional Review Board approval. Proximal tibias were encased with specimen-specific molds for rigid fixation to a 6-degree-of-freedom robot end-effector. Infrared marker clusters mounted to the tibia, fibula, talus, calcaneus, navicular, cuboid, 1st metatarsal, and 5th metatarsal were tracked using motion capture (Optotrak Certus, NDI). Weight-bearing computed tomography (CT) scans were acquired using a Curvebeam PedCAT scanner (120 kVp, 5 mAs, 0.4 mm isotropic) to register the individual transformations between marker clusters and local bone coordinate systems defined by our Automatic Anatomical Foot and Ankle Coordinate Toolbox (AAFACT) [6]. During passive range of motion testing, each specimen was loaded to 25 % body weight in a neutral position and prescribed tibial dorsiflexion/plantarflexion motion under six conditions: (1) flat, (2) 45° toe wedge for metatarsophalangeal joint dorsiflexion, (3) 0.5-in block under 1st metatarsal, (4) 0.5-in block under 5th metatarsal, (5) 10° eversion, and (6) 10° inversion. Tibiotalar, tibiofibular, subtalar (ST), talonavicular (TN), and calcaneocuboid (CC) joint rotations were calculated for each condition and normalized to initial joint angles measured in the loaded, neutral position on the flat surface. One-way repeated measures ANOVA temporal statistical parametric mapping (SPM) analysis ($\alpha = 0.05$) compared individual joint rotations across all conditions followed by post hoc pairwise comparisons with Bonferroni correction using the spm1d package (MATLAB R2023a, MathWorks) [7].

RESULTS: ST and TN transverse and coronal kinematics were generally different between flat and every other condition during the transitions between peak prescribed dorsiflexion and plantarflexion. CC sagittal and coronal kinematics were generally different between flat and every other condition during most of the prescribed motion except for 10° eversion and 10° inversion compared to flat. ST sagittal kinematics were more dorsiflexed with 10° eversion compared to flat during peak prescribed dorsiflexion. TN sagittal kinematics were more dorsiflexed with 45° toe wedge compared to flat, but more plantarflexed with block under 5th metatarsal compared to flat. CC sagittal kinematics were more dorsiflexed with 45° toe wedge, block under 1st metatarsal, and 10° inversion compared to flat, but were more plantarflexed with block under 5th metatarsal and 10° eversion compared to flat. ST and TN transverse kinematics were more internally rotated with 45° toe wedge and 10° inversion compared to flat, but more externally rotated with block under 5th metatarsal and 10° eversion compared to flat. ST transverse kinematics were more internally rotated with block under 1st metatarsal compared to flat, but TN transverse kinematics were not significantly different between flat and block under 1st metatarsal. CC transverse kinematics were more internally rotated with 45° toe wedge and more externally rotated with block under 5th metatarsal compared to flat. ST, TN, and CC coronal kinematics were more everted with block under 5th metatarsal and 10° eversion compared to flat, but were more inverted with 45° toe wedge, block under 1st metatarsal and 10° inversion compared to flat.

DISCUSSION: Hindfoot motion is multifaceted and plays a crucial role in various aspects of gait biomechanics and overall foot and ankle function. This study demonstrated how the hindfoot joints adapt and compensate for forefoot and ankle perturbations, emphasizing the significant contributions the hindfoot

joints provide in the mobility of the foot and ankle. Hindfoot motion enables the foot to adapt to changes in terrain, such as walking on slopes, uneven surfaces, or unstable ground. This study, for example, showed how the mobility of the ST joint adjusted with changes to the orientation of the forefoot and ankle relative to being loaded on a flat surface. The CC joint, which is usually believed to have little motion, showed significant compensatory motion in the sagittal and coronal plane in response to forefoot and ankle perturbations.

SIGNIFICANCE: Data provided in this study can enhance our interpretation of individual joint function and their interactions with each other in the foot and ankle complex. Individual bone motions can be important measures to investigate pathologies and inform surgical outcomes.

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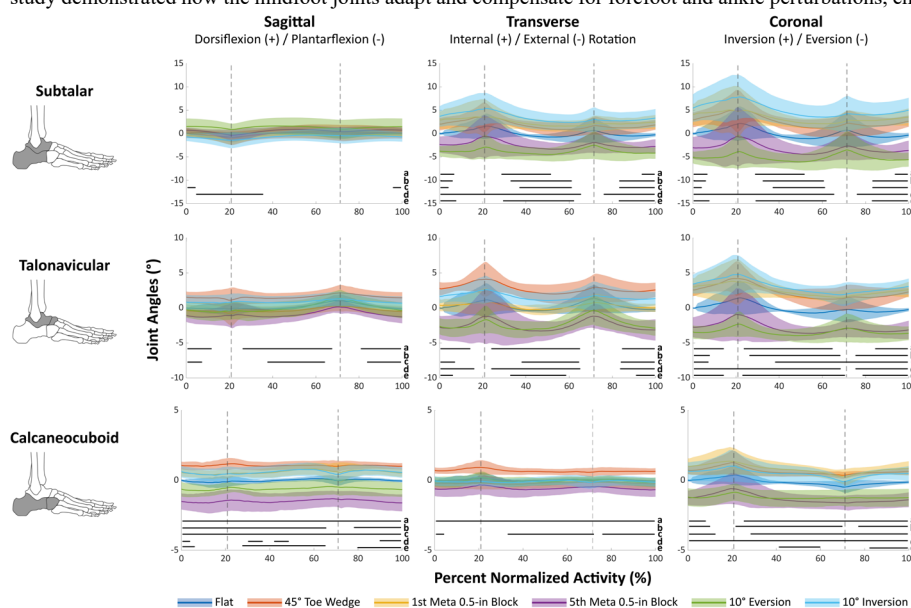


Figure 1: Mean (\pm SD) ST, TN, and CC joint kinematics in the sagittal, transverse, and coronal plane during prescribed tibial dorsiflexion/plantarflexion motion for each condition. Shaded regions indicate 95% CIs. Black horizontal bars indicate portions of prescribed motion where joint kinematics were significantly different between flat versus (a) 45° toe wedge, (b) 0.5-in block under 1st metatarsal, (c) 0.5-in block under 5th metatarsal, (d) 10° eversion, and (e) 10° inversion. First grey vertical dashed line indicates peak prescribed dorsiflexion; second grey vertical dashed line indicates peak prescribed plantarflexion.