Effect of Fifth Metatarsal Perturbation on Hindfoot Vertical Ground Reaction Forces Within a Robot Driven Tibial Coronal Alignment Envelope

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INTRODUCTION: Forces and moments involved during different underfoot conditions are not largely understood; thus, improved descriptions of foot and ankle compensatory mechanics can better inform clinical understanding. The foot's plantar surface continuously interacts with the ground: creating 3-D ground reaction forces (GRFs), free moment, and dynamic pressure distributions [1]. Underfoot conditions are known to affect force distributions from the ankle to forefoot and vice versa [2]. GRFs are important for asserting *in vivo* foot biomechanics *in vitro* during robotic studies [1]. Robotic manipulators allow for integration of more invasive, but accurate, methods invaluable for understanding the small complex structures in the foot and ankle [3, 4]. Furthermore, cadavers allow for repeated and controlled application of invasive procedures. The purpose of this study was to evaluate the changes in the force distributed at the hindfoot when the forefoot and ankle are perturbated with different underfoot conditions using robotic manipulation within a cadaveric model.

METHODS: Five fresh-frozen tibia-to-toe tip cadaveric specimens (5 males; age = 53 ± 13 yrs. old) without prior injury, conditions, and surgeries were procured. Proximal tibia was rigidly affixed to the end-effector of a 6-axis robot manipulator via specimen-specific fixation. Each specimen underwent six underfoot conditions: motion on a (1) flat surface, (2) 45° toe-wedge to prescribe dorsiflexion at the metatarsophalangeal (MTP) joint, (3) 0.5-in block under 1st metatarsal, (4) 0.5-in block under 5th metatarsal, (5) 10º inversion, and (6) 10º eversion. Specimens were loaded to 25% body weight (BW) in a neutral, dorsiflexed, and plantarflexed tibial pose. Specimens were prescribed dorsiflexion/plantarflexion (DPF), varus/valgus rotations (VVS), and external/internal rotation (EIR) motions. A custom platform for prescribing eversion and inversion integrated with three force transducers was used to measure forces and moments at the 1st ray, 5th ray, and heel. Kinetic data was processed and normalized to percent activity. Forces and moments were normalized to percent BW and percent BW*height respectively. One-way repeated measures ANOVA statistical parametric mapping (SPM) analysis ($\alpha = 0.05$) compared heel vertical ground reaction forces (vGRF) across all underfoot conditions followed by post-hoc pairwise comparisons with Bonferroni correction were conducted via the spm1d package (MATLAB R2023a, MathWorks) [6].

RESULTS SECTION: Vertical ground reaction forces were generally significantly different between the 0.5-in raised 5th metatarsal and all other conditions at peak prescribed valgus with dorsiflexed and plantarflexed tibial alignments except for 10º eversion during prescribed valgus with neutral alignment. Peak calcaneal vGRF were consistently greater in 0.5-in raised 5th metatarsal compared to every other condition during prescribed valgus for neutral, plantarflexed, and dorsiflexed tibial alignments. Prescribed VVS vGRF were greatest during the dorsiflexed position and lowest during the plantarflexed position. Plantarflexed VVS vGRF showed significant differences in 0.5-in raised 5th metatarsal compared to all other conditions during the transitional windows of peak valgus. Significant differences were observed between 0.5-in raised 5th metatarsal compared to 10º eversion and 45° toe-wedge after peak varus in plantarflexed tibial position. Peak varus vGRF did not show any significant differences between 0.5-in raised 5th metatarsal compared to all other conditions, but 0.5-in raised 1st metatarsal vGRF were larger than the 0.5-in raised 5th metatarsal during neutral and dorsiflexed alignments.

DISCUSSION: This study exhibited the changes in force distribution at the hindfoot due to various forefoot and ankle perturbation, highlighting the hindfoot's contribution to the overall adaptability of the foot and ankle. This study demonstrated the compensatory vGRF at the heel as the orientation of the forefoot and ankle changed. Increased vGRF during valgus rotation indicates increased distributed vertical loads at the heel particularly during perturbation of the 5th metatarsal. The data provided here can help improve our understanding of the compensatory mechanics at the ankle given varus/valgus rotation and 5th metatarsal pronation.

SIGNIFICANCE/CLINICAL RELEVANCE: This study helps surgeons and scientists by informing of the kinetics involved in the foot and ankle during different underfoot conditions undergoing motion with specific tibial alignment. Varus and valgus deformities with ankle osteoarthritis are prone to poor outcomes and failure after total ankle replacement (TAR) depending on the degree of malalignment [5, 7]. Characterizing the force distributions due to joint compensations involved during varus and valgus motion may inform ankle alignment in TAR for improved clinical outcomes.

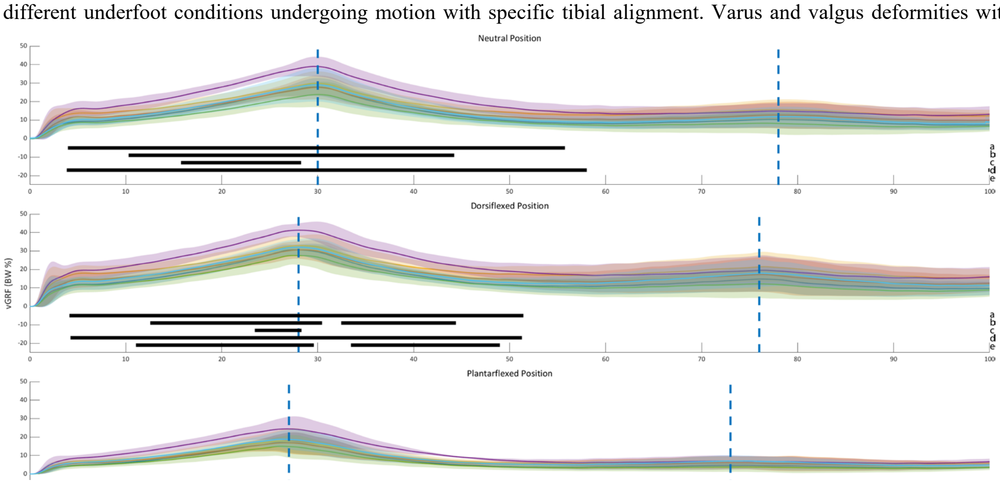

Figure 1: Mean (± SD) vGRF during prescribed VVS in neutral, dorsiflexed, and plantarflexed positions for each condition. Black horizontal lines indicate regions during prescribed motion where hindfoot vGRF were significantly different between underfoot conditions with 0.5-in block under 5th metatarsal 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 dashed light blue line indicates peak prescribed valgus; second dashed light blue line indicates peak prescribed varus.

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