# Development of a Human Foot-Ankle Surrogate for Use in Footwear Testing Methodology

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## ABSTRACT

*Acute musculoskeletal injuries, such as lateral ankle sprains, are prominent lower-limb injuries seen during military fitness training programs. While military combat boots are assessed for a variety of conditions determining effective performance to slip resistance, tolerance to heat and cold, sole flexion, and toe compression, the current footwear evaluation methodology lacks quantifiable ankle-support metrics. A footwear stability test using a surrogate model with representative foot-ankle response is required to objectively evaluate ankle-support offered by combat boots. Currently, there exist several anthropomorphic testing devices (ATDs) that were developed to predict lower limb injury to humans during high-load vertical blast or frontal impacts. Previous work assessed the THOR 50th percentile male, Hybrid III 50th percentile male, and Hybrid III 5th percentile female ATDs against an ongoing volunteer study collecting dynamic ankle stiffness at 1 m/s. Those results demonstrated the need for an improved foot-ankle surrogate representing human response in this application. A surrogate model with representative human ankle response that integrates with a robotic system to evaluate lateral support of footwear is proposed.*

## INTRODUCTION

Acute musculoskeletal injuries, such as lateral ankle sprains, account for 77% of reported lower-limb injuries during military fitness training programs (Kucera et al. 2016; Brian Waterman et al. 2010; House et al. 2013). When the lateral ligamentous structures of the ankle joint are exposed to repetitive and cumulative microtrauma, chronic ankle instability arises in 70% of individuals (Gribble 2019; Hertel 2002; Herzog et al. 2019). Medical discharges due to these injuries alone costs the US military millions of dollars (RL, C, and AE 2016).

Military combat boots are tested in a variety of configurations to determine: slip resistance, toe compression, tolerance to heat and cold, and sole flexion; however, the current footwear evaluation methodology lacks quantifiable ankle-support metrics. Combat boots are designed with an upper eight inches high that primarily provides ankle support. The US Army standardizes a limited number of commercial boot styles for service members to wear. Variations in boot-upper height and material creates considerable differences in ankle support among the different models.

A quantitative lateral-stability assessment with a surrogate model representative of the foot-ankle response is required to better understand the interface between the human foot-ankle and footwear. This type of assessment will inform performance requirements for combat boots, and future research correlating ankle support and injury can be investigated.

There exist several anthropomorphic testing devices (ATDs), also referred to as crash-test dummies, that were developed to represent the human body and predict lower limb injury to humans during high-load vertical blast or frontal impacts. The THOR 50$^{th}$ percentile male, Hybrid III 50$^{th}$ percentile male, and Hybrid III 5$^{th}$ percentile female ATDs were assessed for accuracy of representing human behavior against an unbooted-volunteer study evaluating 27 females and 25 males during quiet standing and gait at 1m/s (Polich et al. 2022). The ATDs were tested under identical unbooted conditions yielding peak stiffness values for plantar flexion, dorsiflexion, inversion, and eversion that were statistically different from the average peak stiffness response of the human volunteers. Those results demonstrated the need for an improved human foot-ankle surrogate in this application. The aim of the current study was to develop a surrogate model representing the human ankle response and integrate this surrogate into an automated testing methodology for measuring the lateral stability of footwear.

## METHODS

### Surrogate Construction

*Joint Behavior*. Average peak stiffness ± standard deviations (Nm/°) in plantar flexion, dorsiflexion, inversion, and eversion were reported as: 1.77 ± 0.2; 1.44 ± 0.3; 1.64 ± 0.1; and 1.54 ± 0.2, respectively (Polich et al. 2022). Average range of motion (ROM) ± standard deviations (°) in plantar flexion, dorsiflexion, inversion, and eversion were reported as: 35.3 ±10; 13.4 ± 6.0; 35.1 ± 10; and 29.9 ± 13, respectively (Polich et al. 2022). These data were used to determine the shape and placement of the ROM rubber bumpers and used to validate the unbooted surrogate response.

*Surrogate Design*. The internal structure of the surrogate consisted of an aluminum shaft, chosen for its strength and machinability, coupled to a universal joint that functioned as the tibia and axes of rotation for the ankle complex, respectively. Two universal joints were tested; one commercially available stainless-steel universal joint (McMaster-Carr Supply Company) and one was 3D printed in clear resin (Form3B Printer, Formlabs). A universal joint provided two degrees of freedom of rotation and tunable stiffness was created by 3D printing 50A shore elastic rubber resin into bumpers that fit onto the axes of the joint (Villwock et al. 2009). These bumpers also served to define the previously determined limit for ROM in plantar flexion, dorsiflexion, inversion, and eversion for the ankle joint complex. A size 9M plastic prosthetic foot covering (Kingsley MFG Company) fit over the universal joint and functioned as the surrogate's foot. This prosthetic foot model was chosen for its design to mimic the human anatomy and to fit into walking shoes. To fill the upper portion of the boot that laces about 8 inches up the front of the shin, an inflatable rubber sleeve will be constructed and coupled to the aluminum stock of the surrogate's tibia.

*Surrogate-Robot Interface.* A custom attachment was machined to couple the surrogate's proximal tibia to a 6ADF80B-Q11 6-axis load cell (Interface Force Measurement Solutions). The load cell then interfaced with the wrist of a RS007A robotic arm (Kawasaki Robotics, Inc.). This robotic arm carries a 7kg payload, velocity of 12 m/s, and 930mm of reach. The capabilities of the robotic arm provide the ability to simulate loading experienced during human gait at 1 m/s and explore lateral motion seen during ankle injury. Once attached to the robotic arm and load cell, the surrogate is booted and secured to the floor using snowboarding boot bindings.

## RESULTS

Several iterations of the surrogate were processed. Initially, a commercially-available universal joint was obtained to quickly prototype a lower extremity design (Figure 1). The Kingsley prosthetic foot fit well into a men's 9M combat boot meaning the boot heel cup did not slip and the boot could be laced securely. In the second iteration, the prosthetic foot was hollowed to allow the universal joint center of rotation to sit at the proper anatomical height at 6.5 cm off the floor (Figure 2). The center of joint rotation was still 5 mm superior to the anatomical equivalent measured at the lateral malleolus, and it did not limit motion to an anatomically-correct ROM. So, a lathe was used to remove 5 mm of height and replaceable bumpers were 3D printed in 50A shore hardness rubber to create the proper ROM limits. Incorporating the commercially-available universal joint with the prosthetic foot demonstrated the need to design a custom ankle joint as the housing of the prosthetic foot interfered with joint motion.

The 3D printed universal joint improved upon the second iteration by allowing custom dimensions to reflect the average anatomic shape of: the ankle height measured from the floor to the lateral malleolus; the ankle length measured from the heel to the front of the ankle; and the bimalleolar width measured between the lateral and medial malleoli (Figure 3).

Figure 1: Surrogate prototype version 1. Lateral view with arrows indicating universal joint center of rotation and top view close up.

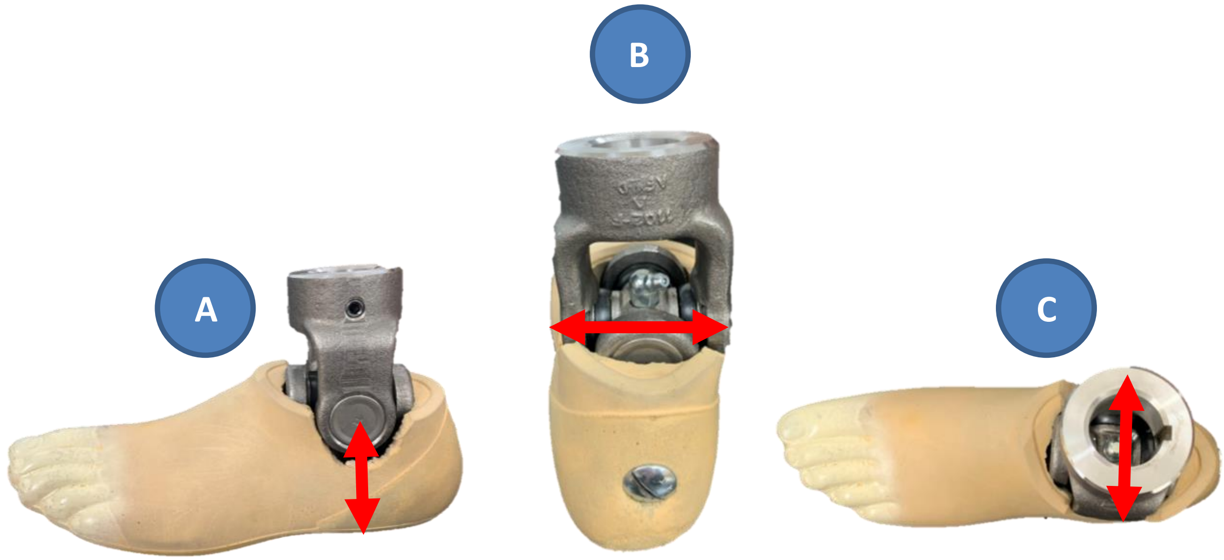


Figure 2: Surrogate prototype version 2. A) Lateral view arrows indicating center of rotation equivalent at lateral malleolus B) Posterior view arrows indicating anatomical equivalent bimalleolar width C) Top view arrows indicating anatomical equivalent bimalleolar width

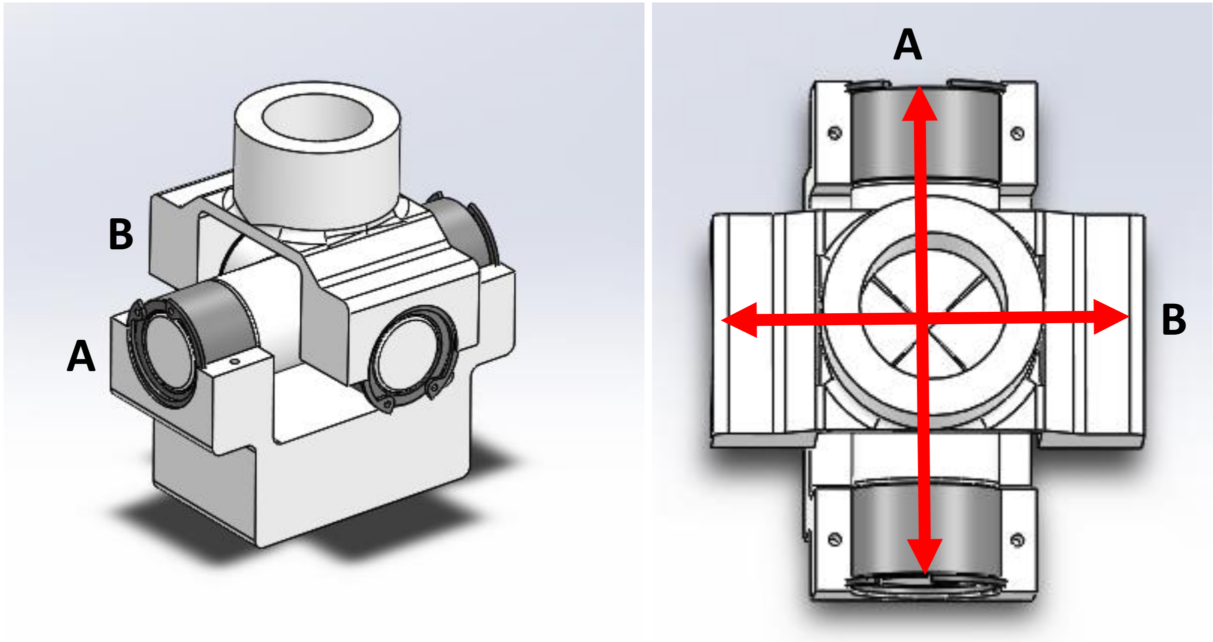


Figure 3: 3D printed universal joint for prototype version 3. A) Anatomical equivalent for ankle length B) Anatomical equivalent for bimalleolar width

## DISCUSSION

In development of the third prototype iteration, Kingsley discontinued the production of our selected prosthetic foot model. A new prosthetic housing is being sourced (Hanger Clinic Charlotte) and will be tested with the 3D printed universal joint. Assembly of the next foot-ankle surrogate prototype will be ready for validation testing in the Biodex following the same methodology used to assess the unbooted ATDs and unbooted human subjects (Polich et al. 2022). The stiffness response of the surrogate will inform whether the response matches that of the human subjects or needs further iterations until a biofidelic foot-ankle surrogate is achieved. Future iterations will include modifications to the 50A rubber bumpers and possibly components of the universal joint. The final ankle-support testing methodology will consist of the robotic arm generating lateral motion and a load cell measuring axial loads and moments at the ankle joint in unloaded and loaded conditions. Stiffness (Nm/°) will be derived from torque and position measurements. These data will be used understand the interface between the human foot-ankle and combat boots so ankle-support requirements for combat boots may be quantified7.

## CONCLUSIONS

In order to quantify human foot-ankle response and interaction with footwear in a laboratory setting, a representative model of the foot-ankle is required. While ATDs are excellent models of human behavior in high velocity scenarios such as frontal impacts and vertical blasts, current models of ATDs were tested and found to be poor surrogates for the human ankle under low-velocity loading seen in gait at 1 m/s. A surrogate was designed to represent human ankle stiffness and ROM in plantar flexion, dorsiflexion, inversion, and eversion. The surrogate consisted of: a custom 3D printed universal joint providing rotation at the anatomically equivalent center of rotation; 50A shore hardness rubber bumpers creating stiffness and ROM limits for the joint; an aluminum shaft representing the surrogate's tibia; and a prosthetic foot covering for the surrogate's foot. This surrogate will be implemented in an automated lateral-stability testing methodology for footwear that includes a robotic arm to generate human gait loading patterns and a 6-axis load cell to collect moment and axial force data. This novel testing methodology will provide quantitative metrics the address goal of understanding the boot-to-ankle interface and the influence of boot design on lower limb microtraumatic musculoskeletal injuries.

## ACKNOWLEDGEMENTS

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