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

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Introduction

Acute musculoskeletal injuries, such as lateral ankle sprains, account for 77% of reported lower-limb injuries during military fitness training programs.[1-3] While military combat boots are tested in a variety of configurations to determine slip resistance, tolerance to heat and cold, sole flexion, and toe compression, the current footwear evaluation methodology lacks any ankle-stability assessment. To reduce lower-limb injuries, a surrogate model with representative foot-ankle response is required for footwear lateral stability testing. 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. To be considered as potential surrogates, the THOR 50th percentile male, Hybrid III 50th percentile male, and Hybrid III 5th percentile female ATDs were assessed for accuracy of representing human behavior in lower-velocity scenarios (<120°/s). From those results, the need for an improved human foot-ankle surrogate was demonstrated. A novel surrogate model with representative human ankle response and ability to be evaluated for lateral stability footwear testing is proposed.

Methodology

Bilateral stiffness (Nm/°) and range of motion (°) data from fifty-two healthy volunteers (25 male/27 female) with no pre-existing ankle conditions were used to inform the expected unloaded behavior of the human foot-ankle complex in plantar flexion, dorsiflexion, inversion and eversion.

The internal structure of the surrogate consisted of an aluminum shaft coupled to a universal joint that functioned as the tibia and axes of rotation for the ankle complex, respectively. The universal joint provided two degrees of freedom of rotation and tunable stiffness. Stiffness of the universal joint was created by 3D printing 50A shore elastic rubber resin (Formlabs, Form3B Printer) into bumpers that fit onto the axes of the joint.[4] These bumpers also served to define the desired limit for range of motion in plantar flexion, dorsiflexion, inversion, and eversion for the ankle joint complex. A size 9M prosthetic foot (Kingsley MFG Company) was modified to fit the universal joint and function as the surrogate's foot. To fill the upper of the boot that laces about 8 inches up the front of the shin, an inflatable rubber sleeve was constructed and coupled to the aluminum stock of the surrogate's tibia.

Results and Conclusions

Table 1: Average Peak stiffness data (Nm/°) and p-values comparing ATD to human response.

	Plantar Flexion	**p-value**	**Dorsiflexion**	**p-value**	**Inversion**	**p-value**	**Eversion**	**p-value**
Human Volunteers (n=52)	1.77 ± 0.2	-	1.44 ± 0.3	-	1.64 ± 0.1	-	1.54 ± 0.2	-
THOR Male	2.6	*<0.0001	3.2	*<0.0001	1.4	*<0.0001	1.7	*0.0062
H3 Male	1.9	*0.0286	2.8	*<0.0001	1.8	*0.0001	1.9	*<0.0001

H3 Female	2.3	*<0.0001	1.6	*0.0060	1.6	0.0900	1.9	*<0.0001

*significance at α=0.05

This surrogate will be validated in the Biodex following the same methodology used to assess the ATDs and human subjects. With further iterations, a more biofidelic foot-ankle surrogate will be designed for use in laboratory stability testing methodology appropriate for the evaluation of footwear. The testing methodology will consist of integrating this surrogate with a Kawasaki Robot model RS007 (Kawasaki Robotics, Inc.) and a 6 axis load cell (Interface, Inc.) capable of measuring axial loads and moments at the ankle joint in unloaded and loaded conditions. Stiffness (Nm/°) will be derived from torque and position measurements.

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