SHORT COMMUNICATION: STAPP CAR CRASH CONFERENCE

Low-Rate Ankle Stiffness in Human Volunteers

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ABSTRACT – Military footwear design provides important foot and ankle support for military personnel. To assess these features, an ankle-support testing methodology and a foot-ankle surrogate must be developed. Fifty-two healthy volunteers (25 male/27 female) with no history of prior ankle surgery, ankle sprain, or fracture were recruited. Their ankle stiffness (Nm/°) and range of motion (°) was quantified during low-velocity testing speeds to define the appropriate response for a human foot-ankle surrogate. The THOR 50th percentile male, Hybrid III 50th percentile male, and Hybrid III 5th percentile female anthropomorphic testing devices (ATD) were also evaluated against the human subject responses for biofidelity in plantar flexion, dorsiflexion, inversion, and eversion. The ATD models' responses were statistically different from the human volunteer population responses. A more biofidelic foot-ankle surrogate should be designed and validated for use in ankle stability-testing methodology for evaluating footwear under these conditions.

INTRODUCTION

Lateral ankle sprains (LAS) are acute musculoskeletal injuries accounting for 73.6% of reported lower-limb injuries seen during military physical readiness training programs (Waterman 2010, Kucera 2016). Repetitive exposure to LAS damages the lateral ligamentous support of the ankle joint and leads to chronic ankle instability in 70% of individuals with a history of LAS (Gribble 2019, Hertel 2000). The US military loses millions of dollars each year due to medical discharges from overuse injuries in training initial recruits (Chalupa 2016). Residual symptoms after LAS can limit the activity of military trainees from 6 weeks to 18 months (Herzog 2019, Orr 2014).

The THOR and Hybrid III are anthropomorphic testing devices (ATDs) designed for automotive crash injury and have not been assessed for biofidelity of the ankle response at loading rates less than 12 m/s (Quenneville 2017, Rudd 2003). While these ATDs have been assessed using Post Mortem Human Surrogate (PMHS) data, they lack biofidelity assessments at low-rates using human subjects. To assess military footwear in lateral bending and stability, an appropriate foot-ankle surrogate with biofidelic ankle joint mechanics and representative foot anatomy must be used to develop an objective measure of the interface between the foot-ankle complex and military issued footwear. The aim of the overall study was to examine ankle stiffness and range of motion in a healthy, young adult population to define the appropriate response corridors for a human foot-ankle surrogate to be used during low-velocity testing to the ankle joint complex. Once human response was established, the response of existing automotive ATDs was also quantified to determine if these ATDs would be to assess ankle lateral stability for different types of footwear.

METHODS

Fifty-two healthy volunteers (25 male/27 female) with no history of prior ankle surgery (osseous or ligamentous) and no history of prior ankle sprain or fracture were recruited for the study. All subjects gave written informed consent approved by the institution's IRB board under IRB00066753. Average subject characteristics were height: 172.72 ± 10.92 cm and weight: 72.12 ± 15.01 kg. Target age was between 18 and 25 with participant average age 23.1 ± 1.5 years. Male subject characteristics were: height 180.24 ± 7.39 cm, weight: 83.61 ± 10.72 kg, age 23.52 ± 1.50 years. Female subject characteristics were: height

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164.81 ± 7.76 cm, weight: 60.59 ± 9.22 kg, age 22.71 ± 1.44 years.

Subjects were reclined in a Biodex isokinetic dynamometer (Model number 835-210, Biodex Medical Systems, Inc.) with 90° hip flexion and 45° knee flexion so that the tibia was parallel to the floor. The thigh was stabilized using a Velcro strap and the tested foot was secured to the foot plate to isolate the ankle joint complex. From this position, each subject's ankle range of motion was quantified in four kinematic movements: plantar flexion, dorsiflexion, inversion, and eversion. To prevent injury, the subjects were allowed to self-select their range of motion. To complete this task, they were required to move their ankle through a comfortable range of motion for them. During the evaluation of the range of motion, no torque values were recorded because it was not passive motion.

The testing methodology consisted of 15 repetitions performed at 5°/s and at 60°/s within the subject-specific range of motion. An angular velocity of 5°/s was selected as representative of intrinsic ankle stiffness response seen during quiet standing (Sakanaka 2018) and 60°/s for gait at 1m/s (Mentiplay 2018). During these measurements, the subjects were instructed to relax the muscles of their legs while the Biodex passively moved their ankle and recorded a torque response. To prevent injury, only the volunteer selected range of motion was used with an electronic and mechanical stop to prevent motion beyond that range. The researcher collecting data also had the ability to stop the machine at any time with an emergency stop button. The same tests and procedures were performed with legs from the THOR 50th percentile male ATD, the Hybrid III 50th percentile male ATD, and Hybrid III 5th percentile female ATD. To set the ATD range of motion, the researcher moved the ATD ankle through the range of motion until they met enough resistance that they could no longer move the ankle. ATD models are designed to be representative of the average human response so each leg was tested once. The BioDex sampling rate was 100 Hz and there was no post processing of the moment and rotation data. Average peak stiffness was calculated by dividing the peak moment by the rotation information using custom code in MATLAB (MathWorks, Inc.). Peak moments occurred at the end range of motion. An example of the torque and rotation data is shown in Figure 1.

All statistical analyses were tested at a significance level of α = 0.05. All data sets were tested for normality. For the normally distributed data collected at 60°/s, parametric two-tailed independent student t-tests tested for statistical differences between the stiffness averages of the sex groups for each kinematic movement. For the non-normally distributed data collected at 5°/s, the same differences were assessed using non-parametric Wilcoxon rank sums analyses. Analysis of covariance was used to control for the influence of sex, height, and weight on subject stiffness response. The same non-parametric and parametric analyses were used to test for significance between the human subject stiffness and ATD stiffness responses.

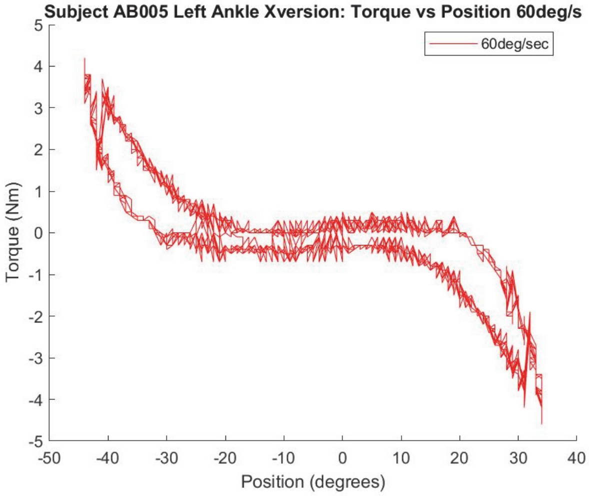

Figure 1: An example of the recorded torque (Nm) and rotation (°) data for a study participant.

RESULTS

Tables 1 and 2 show the range of motion for the human volunteers and the average stiffness response (Nm/°) , respectively, of the human volunteers and Table 3 shows the ATD response. There was not a statistically significant difference between left and right feet mean stiffness values in any of the four kinematic movements for both testing speeds, 5°/s and 60°/s. As a result, only the left-foot data is reported for the following statistical test results. All data collected at 60°/s satisfied the assumptions for a normal distribution and all data collected at 5°/s had a skewed distribution. At 5°/s, there was a statistical difference between male and female groups for kinematic movements. Analysis of covariance showed that there is a relationship between subject sex, height, weight and the stiffness response in dorsiflexion, plantar flexion, and eversion.

At 60°/s, there was not a statistically significant difference between male and female mean stiffness values in any of the four kinematic movements. As a result, the statistical analyses comparing ATD leg

Table 1: Human volunteer range of motion (°, PF = Plantar Flexion, DF = DorsiFlexion, I = Inversion, E = Eversion)

Test speed	Right Ankle				Left Ankle			
Movement	PF	DF	I	E	PF	DF	I	E
All subjects (n=52)	33.6 ± 9.6	-14.5 ± 7.6	-32.2 ± 10.6	33.8 ± 9.3	35.2 ± 10.1	-13.4 ± 6.1	-35.1 ± 9.97	29.9 ± 13.0
Male (n=25)	31.1 ± 10.7	-14.8 ± 8.0	-33.4 ± 11.5	33.4 ± 10.5	34.2 ± 11.1	-14.4 ± 6.1	-36.2 ± 10.9	29.6 ± 7.2
Female (n=27)	36.0 ± 8.1	-14.2 ± 7.5	-31.0 ± 10.0	34.0 ± 8.3	36.4 ± 9.2	-12.4 ± 6.2	-34.1 ± 9.3	30.1 ± 17.0

Table 2: Human volunteer peak stiffness (Nm/°, PF = Plantar Flexion, DF = DorsiFlexion, I = Inversion, E = Eversion)

Test speed	5°/s				60°/s			
Movement	PF	DF	I	E	PF	DF	I	E
All subjects (n=52)	0.53 ± 0.2	0.94 ± 0.3	0.33 ± 0.04	0.42 ± 0.05	1.77 ± 0.2	1.44 ± 0.3	1.64 ± 0.1	1.54 ± 0.2
Male (n=25)	0.78 ± 0.3	1.29 ± 0.3	0.39 ± 0.04	0.50 ± 0.04	1.86 ± 0.2	1.57 ± 0.3	1.70 ± 0.1	1.47 ± 0.1
Female (n=27)	0.30 ± 0.02	0.61 ± 0.2	0.27 ± 0.04	0.34 ± 0.04	1.68 ± 0.1	1.30 ± 0.2	1.58 ± 0.1	1.61 ± 0.2

Table 3: ATD peak stiffness (Nm/°, PF = Plantar Flexion, DF = DorsiFlexion, I = Inversion, E = Eversion)

Test speed	5°/s				60°/s			
Movement	PF	DF	I	E	PF	DF	I	E
THOR M	1.3	1.5	1.2	0.91	2.6	3.2	1.4	1.7
H3 M	0.35	1.6	0.82	1.5	1.9	2.8	1.8	1.9
H3 F	0.62	0.98	0.47	0.45	2.3	1.6	1.6	1.9

response and human subject response looked at the response of the entire volunteer group (n=52). Analysis of covariance showed that there is not a relationship between subject sex, height, weight, and the stiffness response in any kinematic movement.

The average stiffness responses of the entire volunteer group in plantarflexion, dorsiflexion, inversion, and eversion to be statistically different from the THOR 50th percentile male leg responses. This was also true for comparisons against the Hybrid III 50th percentile male leg and the Hybrid III 5th percentile female leg.

DISCUSSION

A difference in the stiffness response between sexes was expected, with men having a stiffer ankle complex than women in previous studies (Orr 2014). The intrinsic stiffness data collected at 5°/s represented ankle response during quiet standing and showed a sex difference. Analysis of covariance additionally supported that a relationship exists between subject sex, height, and weight and the ankle stiffness response in plantar flexion, dorsiflexion, and eversion. These results indicate that if the proposed ankle-stability methodology for footwear is to investigate stiffness during quiet standing, sex-specific surrogates should be used to appropriately represent these different responses. In contrast, the lack of difference in the higher rate assessments suggest that the surrogate does not need to be sex-specific at higher rates.

With an understanding of male and female ankle behavior from the previous data, the biofidelity of ATD legs in low-velocity test scenarios was assessed. During testing speeds representative of quiet standing only the female Hybrid III leg modeled human stiffness behavior in all four kinematic movements for both the male and the female groups. The male and female models of the Hybrid III ATD are manufactured from the same mechanical parts, so a possible influencing factor on stiffness response between these two models is the anatomical differences in foot size. The female Hybrid III foot is smaller and was more challenging to secure on the Biodex foot plate. This could have attributed to artificial stiffness or laxity within certain kinematic motions for the female model.

There was a statistically significant difference between the stiffness data of the volunteer groups and the ATD legs collected at 60°/s. Therefore, the THOR and Hybrid III ATD leg designs do not appropriately model the human foot-ankle response in all four kinematic movements under loading representative of gait at 1m/s.

CONCLUSION

This study successfully characterized the intrinsic and dynamic stiffness responses of young, healthy adult ankles in plantar flexion, dorsiflexion, inversion, and eversion. Depending on the goals of a proposed stability methodology, a sex-specific surrogate would be necessary when characterizing standing stiffness versus dynamic movement of the ankle joint. In the analysis of ATD ankle stiffness for the THOR 50th male, Hybrid III 50th male, and Hybrid III 5th female models, these ATD ankles are not representative of human behavior during low-velocity testing representative of human gait at 1 m/s. Therefore, a more biofidelic foot-ankle surrogate should be designed and validated for use in ankle stability-testing methodology for evaluating footwear under these conditions.

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