SHORT COMMUNICATION: STAPP CAR CRASH CONFERENCE

Sex-Based Differences in Calcaneal Fracture Tolerance under High-Rate Axial Loading

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ABSTRACT – This study examines differences in sex-based criteria for axial loading of the ankle. Seventeen (17) right legs were excised from cadavers representing midsized males (6), large females (6), and small females (5). Each specimen was exposed once to high-rate axial loading (average 4.7m/s within 10ms) at the calcaneus. Axial load was measured at the proximal aspect. High-speed x-ray was used to determine time of fracture, and therefore uncensored fracture load. A strong trend in fracture force reduction from males to females is seen. Statistical significance across groups was observed using ANOVA. Unpaired Student's t-tests disclosed significant differences between midsized males and both large females and small females. Differences between midsized males and large females suggest fracture load is related to sex, not just size. Additional biomechanical data for females are needed.

INTRODUCTION

Women in the armed forces report twice the overall injury rate and a significantly higher rate of stress fractures compared to men (5 – 15% vs. 1 – 3%) (Friedl 2005). Injury data have shown females to be more likely than males to sustain ankle injuries in automotive accidents (Ore 1993). These differences are not solely attributable to overall body size and mass as there is evidence of sexual dimorphism (Nieves et al., 2005).

In studies of ankle fracture tolerance, experimental methods and results are not consistent across previous research. Begeman and Prasad (1990) conducted impact tests using nine pairs of PMHS (Post Mortem Human Surrogate) leg/ankle/foot complexes. Axial load was not found to correlate to injury. Instead, dorsiflexion of 45 degrees was suggested to be an injury threshold (angular rate notwithstanding). Five of the six female specimens were damaged while only one of the twelve male specimens was damaged. Portier et al. (1997) found the ankle to withstand 60 Nm within the joint on average, and 180 Nm peak moment. A 30-degree injury threshold was suggested. Rudd et al. (2004) conducted tests of twenty lower extremities from ten PMHS. Multi-axis load cells were implanted in the tibia and fibula. The average moment and dorsiflexion angle associated with injury (bone or ligament) were 58 Nm and 40 degrees, respectively.

This study was designed to determine the types of ankle fractures produced and force to initial fracture for three groups: small females, large females, and midsized males under highly controlled, repeatable, and high-rate conditions.

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METHODS

Seventeen fresh-frozen PMHS right legs were tested. The characteristics of these PMHS (average age 63 years) are provided in Table 1. The specimens were divided into three groups based upon sex and size: Midsized males (64-106kg and 165-186cm), large females (64-89kg and 161-174cm), and small females (39-63kg and 146-158cm). The large female group (75^{th}-percentile, or 75F) was considered to be a close size analog to the midsized male group (50^{th}-percentile, or 50M), and was chosen to help disclose potential tolerance differences related to sex independent of size. The small female group, or 5F, encompassed the 5^{th}-percentile female population.

The tissues supporting the proximal tibia and fibula were kept intact to preserve anatomical geometry. The tarsals and metatarsals were removed. Approximately 15cm of flesh was removed from above the ankle. All tissue was removed from the plantar surface of the calcaneus. For cutting the legs, specimens were frozen to preserve anatomical conformation. The proximal aspect of the specimens was potted in a square form using Dyna-Cast®. Once thawed, a thin layer of Dyna-Cast® was formed onto the calcaneus (set 20° from horizontal), creating a flat load distribution interface.

Specimens were fixed to a rigid structure and exposed once to high-rate axial loading characterized by nearly constant acceleration and 25.4mm displacement, (average speed of 4.7m/s +/-0.3m/s within 10ms). This loading was applied using a high-energy device (Figure 1) that consists of a rapidly spinning (up to 1000 rpm) inertial mass (454kg) that drives a cam/follower. The spinning cam is driven down to interface with the follower using a pneumatic piston. The follower engages the specimen starting in contact.

Table 1. PMHS characteristics.

PMHS	Group	Age (yr)	Stature (cm)	Mass (kg)	BMI
7409	50M	54	175.3	68.5	22
7575	50M	69	175.3	81.2	26
7542	50M	49	165.1	59.0	22
7805	50M	68	185.4	98.4	29
7406	50M	68	170.2	65.8	23
7849	50M	74	180.3	88.0	27
7469	75F	58	167.6	69.9	25
7380	75F	67	162.6	67.1	25
7618	75F	62	162.6	60.8	23
7058	75F	41	168.9	63.0	22
7834	75F	64	167.6	65.3	23
2366	75F	47	157.5	85.7	35
7607	5F	79	162.6	54.9	21
7630	5F	64	165.1	58.1	21
0509	5F	80	149.9	51.7	23
7727	5F	61	165.1	53.1	19
L7034	5F	67	154.9	54.9	23

A Denton 2513 six-axis load cell was used to measure axial (Fz) reaction force at the proximal aspect of the preparation. The load cell position was adjustable, allowing the calcaneus and tibia of each specimen to be aligned with the follower. A VR Phantom v9.1 camera captured x-ray images (2k fps). Data were collected using a TDAS Pro data acquisition system (20k sps). SAE J211 (SAE, 2014) Channel Frequency Class (CFC) 600 was applied to the load data. Time of fracture was established using visual examination (dimension and intensity changes) of x-ray sequences, and therefore established load at the time of fracture.

RESULTS

The data are plotted and tabulated for comparison both within and across groups. The calcaneus was severely fractured in all tests. Minimum-to-maximum value load-time envelopes are provided in Figure 2. Uncensored calcaneal fracture force and initial fracture time are cataloged in Table 2. Average fracture force is 5.4kN for the 50M group, 4.1kN for 75F group, and 2.9kN for the 5F group. PMHS 2366 was excluded due to an early talus fracture.

Statistical analyses of variance (ANOVA) were conducted to check for significance between groups (Table 3). One-way ANOVA shows significance. Two other analyses of variance (Brown-Forsythe and Welch's), having no assumption of equal standard deviation for each group, also support significance in the difference between means. Unpaired Student's t-tests showed statistical significance between the 50M group and each of the female groups. The two female groups were not statistically different (Figure 3) despite the strong trend.

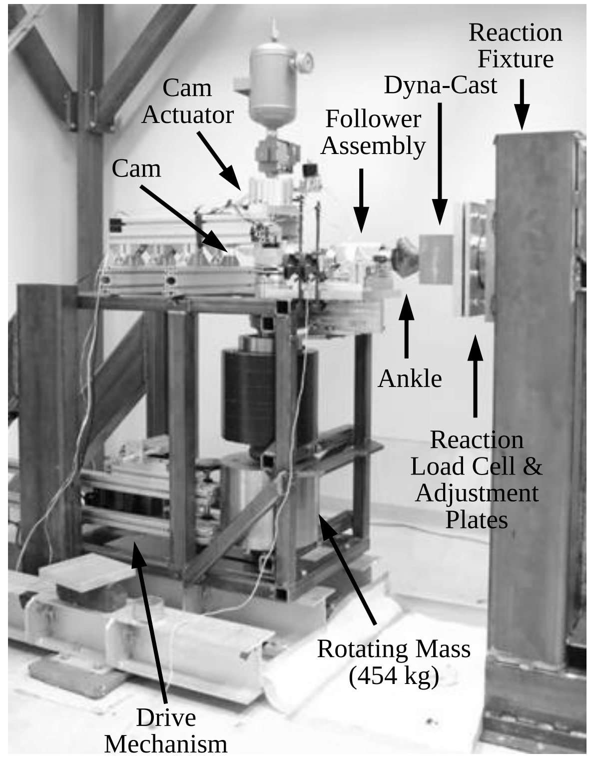

Figure 1. Loading apparatus and test configuration.

Inspection of the x-ray sequences shows the calcaneus and talus tend to move as a unit while the talus rotates at the distal tibia as fracture begins. This was consistent throughout all tests. Importantly, no relationship was found between fracture force and age. Since lumbar bone mineral density was controlled and used as a selection criterion, it was not examined.

DISCUSSION

A unique system was developed to study calcaneus fracture load. This system provides separation of independent and dependent variables, reducing the number of samples required to establish significant results.

A clear trend can be seen in the average fracture forces between the three groups (50M > 75F > 5F), demonstrating important differences between the groups. Three different ANOVA tests disclosed significant differences. Small sample sizes affected the Student's t results, although significant differences were found between males and both female groups. Given the sexual dimorphism of calcanei and tali that have been recorded in the literature, the differences found in this study could be influenced by sex-based structural and material variations. Future analyses will include investigation of the effects of local bone mineral density and joint morphology.

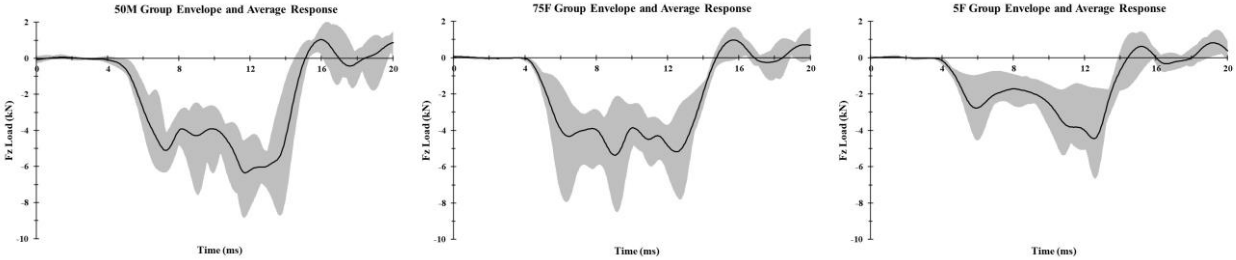

Figure 2. Axial (Fz) response envelopes and average responses (black lines) for the 50M, 75F, 5F groups.

Table 2. Summary of fracture loads and times for all groups.

	50M			75F			5F	
PMHS	Fracture Load (N)	Time (ms)	PMHS #	Fracture Load (N)	Time (ms)	PMHS #	Fracture Load (N)	Time (ms)
7409	-5,032	3.90	7469†	-3,088	4.05	7607	-2,589	2.80
7575	-4,372	4.85	7380	-3,202	3.40	7630•	-960	2.95
7542	-4,891	3.40	7618	-4,763	2.45	0509	-3,218	2.20
7805	-5,578	2.80	7058	-4,003	3.40	7727	-4,544	2.60
7406	-6,333	3.80	7834	-5,593	2.35	L7034	-3,055	2.70
7849	-6,229	2.45	2366‡	-8,504	5.50			
Average Std. Dev.	**-5,406 ±780**	**3.53 ±0.86**	**Average Std. Dev.**	**-4,130 ±1,061**	**3.05 ±0.67**	**Average Std. Dev.**	**-2,873 ±1,293**	**2.65 ±0.28**

† Late pilon Fx ~ 3,689 N, 5.6 ms; ‡ Early talus Fx ~ 7,928 N - not used, 2.65 ms; • Late talus Fx ~ 2,000 N, 7.9 ms

Table 3. Statistical analyses (*p<0.05, **p<0.01).

Statistical Test		p	
ANOVA	One-Way	0.0054	**
	Brown-Forsythe	0.0091	**
	Welch's	0.0156	*
Unpaired Student's t	5F vs. 50M	0.0030	**
	75F vs. 50M	0.0469	*
	5F vs. 75F	0.1315	ns

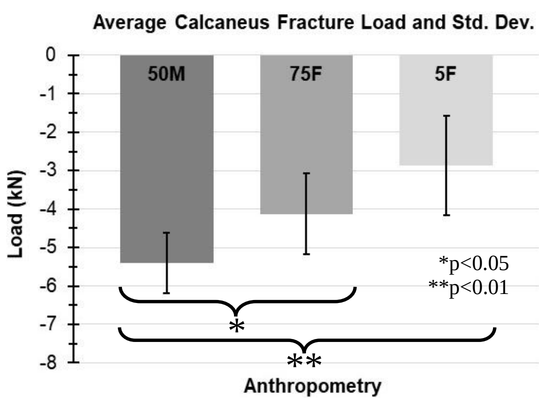

Figure 3. Fracture load trends and significance.

CONCLUSION

In this study, significant differences in uncensored values for calcaneus fracture force were found across midsized males, large females, and small females. Significance was observed between midsized males and both female groups. This indicates differences in ankle fracture tolerance between males and females, and suggests these differences could be related to sex, not just size. Therefore, additional biomechanical tolerance data for females is warranted.

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