Role of Army Combat Boot in influencing calcaneus and distal tibia injuries and risk curves from underbody blast loading

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Abstract. Calcaneus and distal tibia fractures are the most common injuries from underbody loading events. Human cadaver foot-ankle-tibia complexes have been subjected to underbody blast impacts, and tests have been done with and without boot use. While peak forces have been determined for both boot conditions, the role of boots in influencing calcaneus and distal tibia injuries and risk curves has not been determined. The objectives of the study were to analyze our previously conducted tests and delineate the role of the boot for two common types of fractures. Forty-five foot-ankle-lower specimens were subjected to vertical impacts using custom vertical accelerator. For the statistical analysis, the peak force data were used as the primary response variable, and the presence or absence of the boot was treated as a covariate for the two most conservative human injury probability curves (HIPCs). Twenty-seven sustained calcaneus fractures and ten specimens sustained distal tibia fractures. Calcaneus fractures occurred in ten and tibia fractures occurred in nine specimens with the booted condition. The HIPCs based on parametric survival analysis are provided in the paper for the presence and absence of boots for the two most conservative (lower bound) estimates. The boot modulated the forces by approximately ten percent for both conservative estimates of the HIPCs. The plus and minus 95% percent normalized confidence intervals and quality of HIPCs at discrete probability levels are given the body of the paper along with the various HIPCs. The greater occurrence of calcaneus than tibia fractures with the booted condition is in line with the field studies associated with underbody blast environments. Additional tests posture-based studies are needed to delineate the role of posture on the greater occurrence of calcaneus injuries.

1. INTRODUCTION

Combat-related activities have shown that they can result in lower leg injuries in the form of fractures of the calcaneus and or distal tibia complex to military personnel [1-4]. Studies have shown that they can occur from vertical impacts during events such as underbody blast loading from improvised explosive devices [5-8]. This vertical loading mode to the human foot is also prevalent in other scenarios [9, 10]. To investigate the biomechanics of these injuries, describe injury criteria, and develop manikin or anthropomorphic test devices, it is important to conduct impact tests under the vertical loading mode. Unembalmed human cadaver specimens are routinely used for such purposes. These types of tests can be conducted using whole body surrogates or subsystem/component models [11-14]. In the former model, human cadavers have been exposed to blast loading in a field-type environment, and the resulting injuries have been identified to the calcaneus, tibia, and other body regions [11]. In a more controlled setting whole body human cadavers have been exposed to simulated impact loads, and similar injuries have been found. In the latter experimental model, isolated lower leg specimens including the foot-ankle-tibia complex have been subjected to simulated vertical impact loading, and this model produced injuries to the calcaneus, tibia and other bones or joints [13]. The cited literature is not all inclusive. This has formed a primary dataset in the understanding of these injuries from vertical loading to the plantar surface of the human foot, and as applied to military environments.

Whole body human cadaver experimental models described above have included the use of the boot to paralleled field conditions in military scenarios [11]. In contrast, more controlled and focused laboratory studies with the subsystem or component experimental model have evaluated the biomechanics of injury with and without the presence/use of the boot [12, 14-17]. Different researchers have used different types of boots, based on the needs of the study design and intended application [15, 17-20]. The introduction of an energy absorbing material, in this case, the boot, influences the load path

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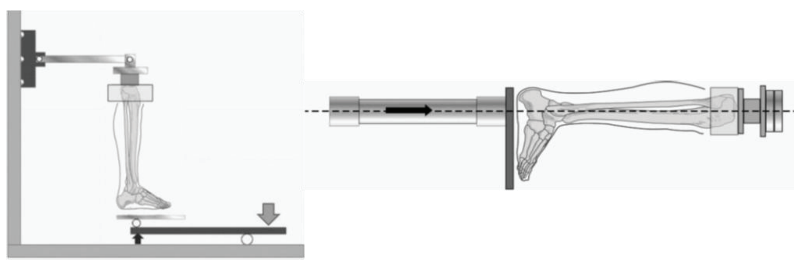
within the foot-ankle-distal tibia fibula complex, i.e., the multiple bones and surrounding joints. The level of influence depends on numerous factors. Some studies have developed injury risk curves for the entire dataset; however, the role of the boot in influencing the impact biomechanics of internal load transfer, injury outcomes and HIPCs has not been investigated. The purpose of the present study is therefore, to determine the role of the boot in modulating the foot-ankle-distal tibia fibula complex injuries and associated risk curves from vertical impacts. The role of the boot in producing the two most common fractures are delineated.

2. METHODS

2.1 Experimental methodology and biomechanical data

Tests were conducted using unembalmed human cadaver foot-ankle-distal tibia fibula complexes. While detailed test information is provided elsewhere, the following descriptions are pertinent to meet the objectives of the present analysis-based study [13]. The specimens were screened for pre-existing fractures, and x-rays and computed tomography (CT) scans were obtained. The foot-ankle-distal tibia fibula complex was at fixed at the proximal end, a six-axis load cell was attached, and a simulated femur was fixed to the load cell in some preparations, based on the device used to apply the impact loading. A military combat boot (Style 3187; McRae or Belleville Footware Inc., Baltimore,MD) was donned in some specimens. Its size was based on the anthropometry of the foot of the specimen. A new boot was used for each specimen. Vertical impact loading was directed along the longitudinal axis of the tibia using one of the two devices: custom vertical accelerator or pendulum (Figure 1).



Figures 1 and 2. Schematics of the specimen with the loading along the longitudinal axis of the tibia in the vertical accelerator (Figure 1a, left) and pendulum (Figure 1b, right) devices.

For tests with the vertical accelerator, the preparations were aligned such that the plantar surface of the preparation, longitudinal tibial axis, and longitudinal axis of the femur were orthogonal to each other before impact, termed as 90-90-90 posture in literature. For tests with the pendulum device, they were aligned in a similar posture in the pendulum device for applying the load that was aligned along the tibia axis with the exception that the simulated femur was replaced by equivalent ballast mass, mounted superiorly to the load cell. Thus, the preparation sustained the intended vertical impact loading vector in both devices, i.e., inferior-to-superior accelerative forces via the plantar surface to unbooted and booted foot-ankle-distal tibia fibula complex preparations. Following the final impact test, the specimens underwent radiography, followed by CT and gross dissection to identify the injuries, and orthopedic surgeons of our team assisted in the assessments of injuries. Fractures to the calcaneus and tibia identified in these experiments were used in the analysis of data, described below. The peak forces recorded by the load cell was identified using the force-time histories, and the fracture outcomes from the pre- and posttest images, described above. Parametric survival analysis techniques were used to construct the human injury probability curves, HIPCs, for the following five groups.

2.3 Grouping for human injury probability curves

Group A consisted of HIPCs for calcaneus fractures without the presence of tibia fractures, i.e., specimens with tibia-only injuries were removed. Group B consisted of HIPCs for tibia fractures without the presence of calcaneus fractures, i.e., specimens with calcaneus-only injuries were removed. Group C consisted of HIPCs associated with the presence of either outcomes, tibia or calcaneus. Group D consisted of HIPCs for calcaneus fractures without the presence of tibia fractures, and specimens with tibia only injuries were considered as no injuries. Group E consisted HIPCs for tibia fractures without

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the presence of calcaneus fractures, and specimens with calcaneus-only injuries were considered as no injuries. All these selection groups have statistical relevance, and they are discussed later.

2.4 Survival analysis

In all cases, specimen outputs considered as non-injury and injury data were treated as right and exact censored observations in the survival analysis. Reasons for selecting this censoring scheme are given in the discussion section. The survival analysis modeling was performed using the R-software (version 3.6.4). The lowest Brier Score Metric, BSM, and its associated distribution were used to calculate the final injury risk curves [21]. The cumulative density functions evaluated in the analysis were the Weibull, lognormal, and log-logistic distributions. The Normalized Confidence Interval Size, NCIS, was defined as the ratio of confidence interval width to the magnitude of the peak force estimate. The NCIS magnitudes of <0.5, between 0.5 and 1, >1 to 1.5, and >1.5 were assigned the adjectival ratings of good, fair, marginal, and unacceptable, respectively [22]. They were reported as tabulated data at 5%, 10%, 25%, 50%, 75%, 90%, and 95% probability levels. First, from the group of five HIPCs, the two most conservative HIPCs serving as the lower bound estimates for calcaneus or tibia injuries were identified. For these two datasets, the effect of the boot was determined by treating its presence or absence in the survival analysis. The boots were treated as a covariate. This process yielded four HIPCs: with and without boots for the two most conservative cases.

3. RESULTS

The mean age and stature of these human cadavers were 56 ± 12 years and 1.79 ± 0.06 m. All specimens were from male human cadavers. The dataset used in the analysis consisted of 45 specimens with calcaneus injuries to 27 and tibia injuries to ten, while the remaining eight specimens did not sustain any injury. Calcaneus fractures occurred in ten and tibia fractures occurred in nine specimens with the booted condition.

3.1 HIPCs from five groups

A comparison of the HIPCs for the five groups of specimens are shown in Figure 3. The quality indices ranged from fair to good at the 5%, 10%, 25%, 50%, 75%, 90%, and 95% probability levels for all risk curves in all groups. Groups A and C were considered as the two most conservative HIPCs. Figure 5 shows the HIPCs and NCIS magnitudes at different probability levels for the group A dataset without the use of the boot. Forces associated with the 10%, 25%, and 90% injury probability levels were 4.4 kN, 7.4 kN, and 10.3 kN, respectively. The quality indices were in the fair, good, and good categories at these probability levels, respectively.

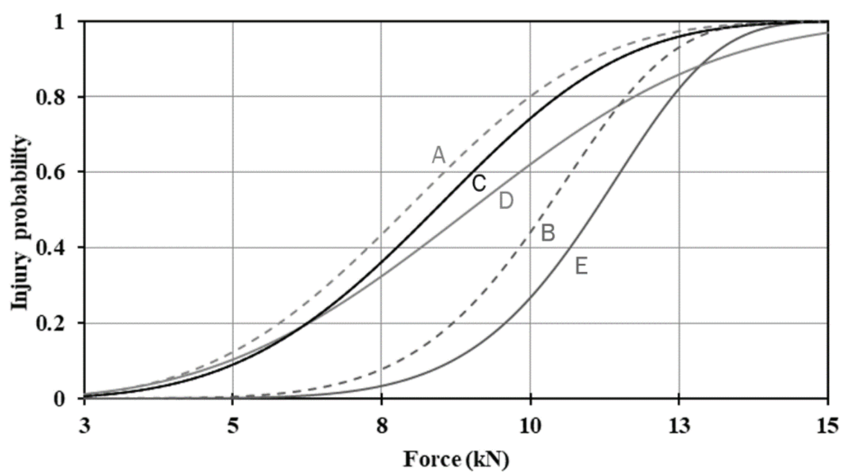

Figure 3. HIPCs for the five groups. See text for grouping details.

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3.2 Boot-based injury probability curves

Group A and group C data were used to determine the role of the boot in this analysis. Figure 4 shows the HIPCs and NCIS magnitudes at different probability levels for the group A dataset without any consideration regarding the use of the boot. Table 1 includes the NCIS and other data.

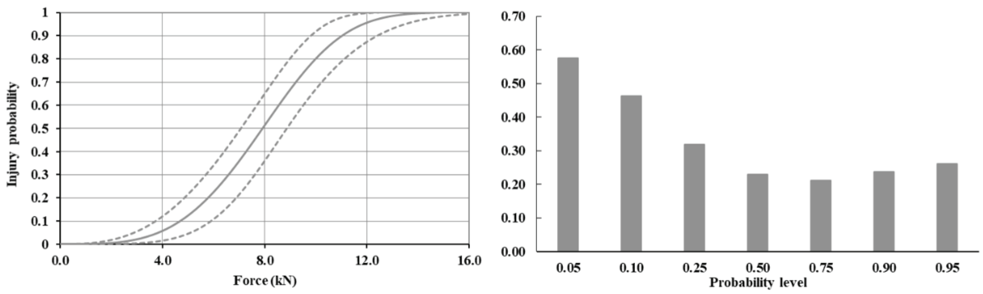

Figure 4. HIPCs for group A without considering the use of the boot as a covariate. Dashed lines show the 95% confidence intervals. Bar chart shows the NCIS at different probability levels.

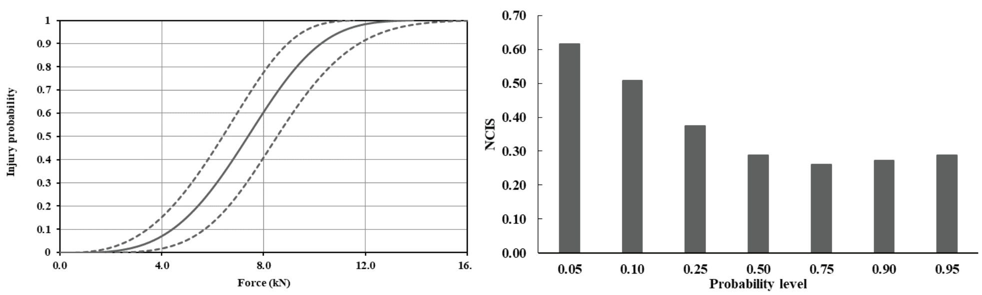

Figure 5. HIPCs for group A without the use of the boot as a covariate. Dashed lines show the 95% confidence intervals. Bar chart shows the NCIS at different probability levels.

Table 1: HIPC data for the group A dataset without the use of a boot

Risk Level	Mean force (kN)	95% Confidence interval		NCIS	Quality index
		Lower bound	Upper bound		
		Group A data			
0.05	3.62	2.67	4.91	0.62	Fair
0.10	4.41	3.43	5.67	0.51	Fair
0.25	5.81	4.82	7.00	0.37	Good
0.50	7.39	6.40	8.53	0.29	Good
0.75	8.94	7.84	10.18	0.26	Good
0.90	10.27	8.97	11.76	0.27	Good
0.95	11.04	9.56	12.74	0.29	Good

Figure 6 shows the HIPCs and NCIS magnitudes at different probability levels for the group A dataset with the use of the boot. Forces associated with the 10%, 25%, and 90% injury probability levels were 5.2 kN, 8.7 kN, and 12.4 kN, respectively. The quality indices were in the good category at these probability levels. Data at other levels are shown in Table 2. Table 3 shows the change in the forces at different probability levels with and without the use of the boot, with respect to the peak forces independent of its use. The following equations were used to determine the percentage changes.

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Table 2: HIPC data for the group A dataset with boot use

Risk Level	Mean force (kN)	95% Confidence interval		NCIS	Quality index
		Lower bound	Upper bound		
		Group A data			
0.05	4.25	3.17	5.69	0.59	Fair
0.10	5.17	4.05	6.62	0.50	Good
0.25	6.81	5.61	8.28	0.39	Good
0.50	8.67	7.30	10.29	0.34	Good
0.75	10.48	8.82	12.46	0.35	Good
0.90	12.04	10.00	14.51	0.37	Good
0.95	12.95	10.64	15.74	0.39	Good

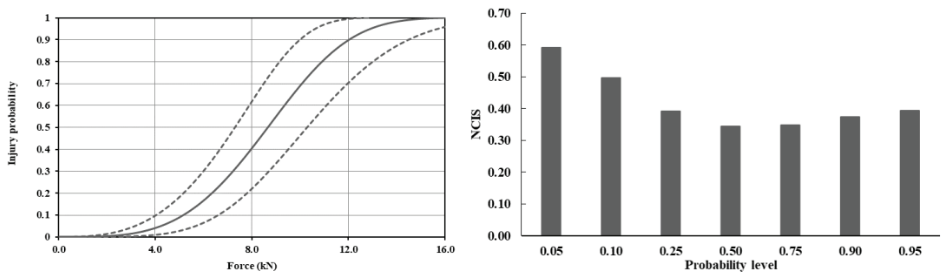

Figure 6. HIPCs for group A with the use of the boot as a covariate. Dashed lines show the 95% confidence intervals. Bar chart shows the NCIS at different probability levels.

$$\%\ change\ with\ boot\ use = 100\ X\ \frac{\text{Force with boot use} - \text{Force independent of boot use}}{\text{Force independent of boot use}} \quad (1a)$$

$$\%\ change\ without\ boot\ use = 100\ X\ \frac{\text{Force without boot use} - \text{Force independent of boot use}}{\text{Force independent of boot use}} \quad (1b)$$

The mean difference across all risk levels for the mean value was 6.5% without boot use and 9.6% with boot use. In other words, at any risk level, the absence or presence of boot modulated (decreased or increased) the magnitudes of forces by approximately 7% and 10% compared to the case wherein the boot effects were ignored.

Table 3: Effect of boots on HIPC magnitudes for group A dataset

Risk level	Mean difference (kN)	% difference	Mean difference (kN)	% difference
	Without Boot		With Boot	
0.05	0.23	-5.9%	0.40	10.4%
0.10	0.29	-6.1%	0.48	10.2%
0.25	0.40	-6.4%	0.61	9.8%
0.50	0.53	-6.6%	0.75	9.5%
0.75	0.66	-6.8%	0.89	9.3%
0.90	0.77	-7.0%	1.01	9.1%
0.95	0.84	-7.1%	1.07	9.0%
Average		-6.5%		9.6%

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Figures 7 shows the HIPCs and NCIS magnitudes at different probability levels for the group C dataset without any consideration regarding the use of the boot. Figure 8 shows the HIPCs and NCIS magnitudes at different probability levels for the group C dataset without the use of the boot. Forces associated with the 10%, 25%, and 90% injury probability levels were 4.7 kN, 7.5 kN, and 10.1 kN, respectively. The quality indices were in the good category at these probability levels. Data at other levels are shown in Table 4. Figure 9 shows the HIPCs and NCIS magnitudes at different probability levels for the group C dataset with the use of the boot. Forces associated with the 10%, 25%, and 90% injury probability levels were 5.8 kN, 9.2 kN, and 12.3 kN, respectively. The quality indices were in the good category at these probability levels. Data at other levels are shown in Table 5. Table 6 shows the change in the forces at different probability levels with and without the use of the boot, with respect to the force magnitudes independent of its use. The mean difference across all risk levels for the mean value was 10.5% without boot use and 9.6% with boot use. In other words, at any risk level, the absence or presence of boot modulated (decreased or increased) the magnitudes of forces by approximately 10% compared to the case wherein the boot effects were ignored.

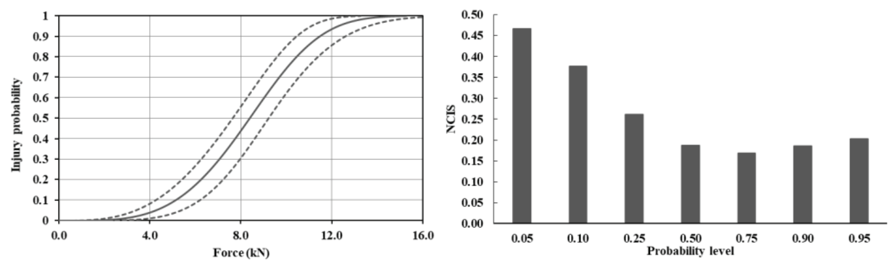

Figure 7. HIPCs for group C without considering the use of the boot as a covariate. Dashed lines show the 95% confidence intervals. Bar chart shows the NCIS at different probability levels.

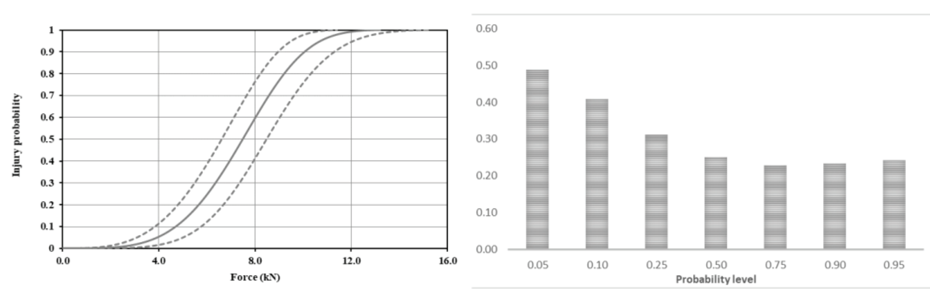

Figure 8. HIPCs for group C without the use of the boot as a covariate. Dashed lines show the 95% confidence intervals. Bar chart shows the NCIS at different probability levels.

4. DISCUSSION

As stated in the introduction, the purpose of the study was to determine the role of the boot in modulating injuries and risk curves to the tibia and calcaneus from vertical impacts simulating underbody blast environments and develop HIPCs. The role was determined using a human cadaver model that consisted of unembalmed human cadaver foot-ankle-distal tibia fibula complexes that were fixed at the proximal end with a load cell to record the peak forces. Fracture outcomes and force data were obtained from injury and non-injury tests and from specimens that were tested with and without the presence of the boot. These form the basic steps for achieving the objectives of the present analysis. The process of using parametric survival analysis has become a de facto norm in impact-injury biomechanics to determine the human tolerance in the form of risk curves [9, 17, 20, 23-27]. Peak forces were used in the development of HIPCs. They were treated as right censored observations for the non-injury and exact censored observations for the injury data points. The reason for selecting the right

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censoring option was that the survival analysis, unlike traditional binary regression, allows this flexibility, and adds statistical content to the ensuing HIPCs. The uncensored option for injury data points was used based on the following reasons. First, the peak force represents the greatest force sustained by the specimen due to the application of the impact load. Second, the injuries observed following the experimentation was associated with this force level. Previous studies using human cadaver foot-ankle complexes have shown that the peak force is associated with injury [17, 19, 28].

Table 4: HIPC data for the group C dataset without boot use

Risk Level	Mean force (kN)	95% Confidence interval		NCIS	Quality index
		Lower bound	Upper bound		
		Group A data			
0.05	3.94	3.10	5.02	0.49	Good
0.10	4.71	3.84	5.77	0.41	Good
0.25	6.03	5.16	7.04	0.31	Good
0.50	7.49	6.61	8.48	0.25	Good
0.75	8.88	7.93	9.96	0.23	Good
0.90	10.07	8.96	11.31	0.23	Good
0.95	10.74	9.52	12.12	0.24	Good

Table 5: HIPC data for the group C dataset with boot use

Risk Level	Mean force (kN)	95% Confidence interval		NCIS	Quality index
		Lower bound	Upper bound		
		Group A data			
0.05	4.82	3.87	6.02	0.45	Good
0.10	5.76	4.79	6.92	0.37	Good
0.25	7.38	6.42	8.48	0.28	Good
0.50	9.16	8.17	10.28	0.23	Good
0.75	10.87	9.72	12.16	0.22	Good
0.90	12.32	10.93	13.89	0.24	Good
0.95	13.15	11.58	14.93	0.25	Good

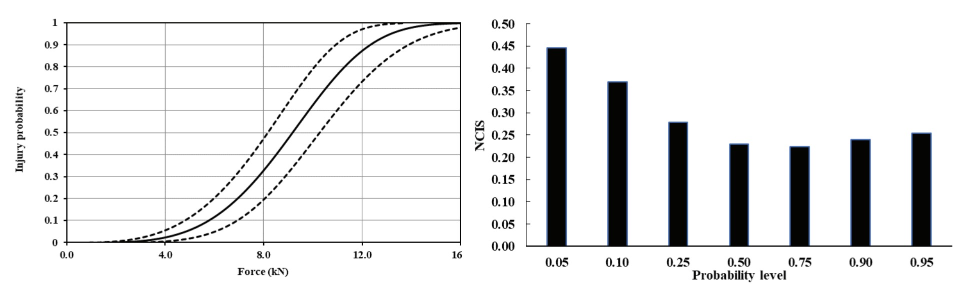

Figure 9. HIPCs for group C with the use of the boot as a covariate. Dashed lines show the 95% confidence intervals. Bar chart shows the NCIS at different probability levels.

Multiple datasets were considered to analyze the biomechanical data and develop the HIPCs (Figure 3). Grouping by the presence of only calcaneus injuries represents the cases wherein the curve is associated and applicable to no other injuries (group A), and this is also true for the grouping of cases with tibia-only injuries. These HIPCs focus on the fracture of the specific bone from vertical loading.

Field data show that this type of fractures occurs in the military environments to Service Members [29]. The grouping of injuries by the tibia-only cases (group B) fall along these lines of discussion. From this perspective, the present study has provided HIPCs specific to these two injuries, treated separately. The cases where the presence of either injury, calcaneus or tibia (group C), represent the HIPCs in which one of these two injuries can be expected and need protection. Because the proximity of the calcaneus to the impact vector and the relatively stronger long bone, HIPCs for tibia-only fractures are right shifted compared to the calcaneus only HIPCs, even when the dataset considered calcaneus-only injuries as no fractures (group E). Likewise, the HIPCs the calcaneus-only fractures are left shifted compared to the tibia-only HIPCs, even when the dataset considered tibia-only injuries as no fractures (group D). These are also in line with the expected outcomes for the choice of the datapoint in the HIPC analysis.

Table 6: Effect of boots on HIPC magnitudes for group C dataset

Risk level	Mean difference (kN)	% difference	Mean difference (kN)	% difference
	Without Boot		With Boot	
0.05	0.32	-7.5%	0.56	13.2%
0.10	0.43	-8.5%	0.62	12.0%
0.25	0.65	-9.7%	0.70	10.5%
0.50	0.91	-10.8%	0.76	9.1%
0.75	1.18	-11.7%	0.81	8.0%
0.90	1.42	-12.3%	0.84	7.3%
0.95	1.56	-12.7%	0.85	6.9%
Average		-10.5%		9.6%

The present study focused on determining the two most conservative HIPCs (lower bound estimates) to determine the role of the boot in modulating the injuries and resulting injury risk curves. This type of analysis led to the identification of group A and group C HIPCs for which the boot was used as a covariate and boot dependent HIPCs were derived. As expected, the HIPCs without boots resulted in lower forces than the HIPCs with boots at the same injury risk level. The differences in the use or nonuse of the boot was however, limited to approximately ten percent when compared to the combined (regardless of the boot presence) datasets, true for both groups A and C (Tables 3 and 5). The present analysis quantifies the modulating role of the boot in shifting the HIPC from left to right (absence to presence of the boot), and it should be noted that the underlying biomechanical tolerance of the bone does not change. That is, bone fractures when it is loaded above its threshold. and any intervening end condition modulates the transmitted force to the bone. In other words, the true fracture force limit does not change and is independent of the end condition (boot use in this case). The changing HIPCs from left to right with the boot shows the greater magnitudes of the impact loading that can be applied to the plantar surface of foot from the no boot to with boot condition, (demonstrating the protective effect of the boot use, an intended feature in the military environment), and in this case, as discussed, it is approximately ten percent across the entire probability curve for the two most conservative HIPCs.

The presence of the boot resulted in more calcaneus fractures than tibia fractures in this experimental study. This suggests that while the boot acts as a medium for transmitting the impact loads and protects the military personnel, calcaneus fractures occur more than tibia fractures. In an analysis of injuries to Warfighters in underbody blast environments, Danelson et al., found that calcaneus fractures were the most prevalent followed by forefoot and distal tibia fractures [29]. The differences between the outcomes of the present series of experiments and field data may be due to the controlled, nominal posture in the PMHS tests compared to varied postures of the Soldiers in the field environment. However, the greater occurrence of calcaneus fractures, in this small sample study, is in line with field outcomes. Additional tests are needed, however, in other postures to delineate the role of posture on the greater occurrence of calcaneus injuries with the use of the boots.

As stated in the methods section, a new boot was used for each leg. While not presented in the manuscript, a separate series of tests was done to determine the attenuation characteristics of the boot. Variations in the attenuation forces were 1.3%, 2.5%, and 3.8% for 3 different boots, all compressively tested 10 times in a material testing device without the presence of the biological surrogate. Thus, the use of the same boot for each specimen when it was repeatedly loaded (interval censoring design of the experiment wherein noninjury and injury tests were done) induced minimal changes to the responses of

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the human cadaver leg. It should be noted, however, that the responses may differ if different types of boots are used. This is a future investigation topic.

Introduction of a boot to the specimen influences the original load path, and the load transmitted to the leg depends on the properties of the boot (expected reduction in amplitude and increase in time). Mass recruitment effects come into play depending on the relative contributions of the amplitude and duration of the applied pulse to the specimen, and in addition, specimen characteristics play a role. Previous whole-body studies that applied inferior to superior acceleration to the pelvis have shown that a lower magnitude and a longer duration pulse tends to injure the lumbar spine while a larger amplitude and a shorter time duration pulse tends to fracture the pelvis [30]. A similar phenomenon is expected although the clear differentiation of the mass recruitment effects, and pulse profiles were not investigated in the present study. This is also a future research topic.

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