Verification of a Calcaneus Fracture Probability Curve in High-Rate Vertical Loading

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I. INTRODUCTION

Fracture to the calcaneus is a known consequence of high-rate vertical loading to the feet of seated occupants in vehicles exposed to under-body blast (UBB) [1-2]. The anatomic alignment between the point of contact at the floor and the leg centre of mass allows for compression of the calcaneus leading to fracture [3]. A study of high-rate vertical loading of the human foot and leg quantified the risk of calcaneus fracture at rates consistent with UBB [4]. Human injury probability curves (HIPCs) for "mild" and "severe" calcaneus fracture were developed from heel contact forces during testing of isolated post-mortem human subject (PMHS) foot-leg specimens. The current study utilised high-rate loading of whole-body PMHS in seated postures to compare injury outcomes to those from foot-leg component testing in order to verify the ability of the HIPCs to predict calcaneus fracture.

II. METHODS

Ten whole-body male PMHS were tested in four series at three facilities: one series using the "VALTS" at Johns Hopkins University Applied Physics Laboratory (JHUAPL), one series using the "WHAM" sled at Wayne State University (WSU), and two series using a drop tower at the University of Michigan Transportation Research Institute (UMTRI) (Table I). Each test facility generated high-rate vertical loading to the seated subject, with floor peak velocity (Peak-V) and time-to-peak velocity (TTP-V) similar to those recorded in prior foot-leg component tests used to create calcaneus fracture HIPCs [4]. Footwear, foot position, and lower extremity joint angles were matched to prior foot-leg component testing. Specifically, whole-body subjects donned army combat boots and were positioned with feet flat on the floor plate, and ankles, knees, and hips at 90 degrees. Floor plate vertical acceleration and reaction forces were collected. Accelerations and rotations of the legs were measured at the anterior tibia and acceleration was recorded at the medial surface of the calcaneus. High speed video captured motion of the test fixture and specimen. Pre-test and post-test x-rays and/or Computed Tomography (CT) images were utilised to evaluate the presence and pattern of fracture to the feet and legs. Cases where a calcaneus fracture was determined to be the primary injury were classified as "mild" (Sanders Type I/II) or "severe" (Sanders Type III/IV) [5]. The same method for classifying calcaneus fracture was used in the prior foot-leg component study.

Table I.
Whole-body tests performed with component floor input conditions for reference.

Test Facility	Type	No. of PMHS	Floor Peak-V (m/s)	Floor TTP-V (ms)	Seat Peak-V (m/s)	Seat TTP-V (ms)
JHUAPL	Whole-body	2	15.5	2.5	10.0	7.5
WSU	Whole-body	2	13.0	2.5	9.0	5.0
UMTRI	Whole-body	3	9.0	2.5	6.0	7.5
UMTRI	Whole-body	3	7.0	2.0	5.0	25.0
Voo *et al.*[4]	Component	19	7.0 – 16.0	1.8 – 3.5	N/A	N/A

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III. INITIAL FINDINGS

Whole-body tests resulted in five isolated severe calcaneus fractures and one isolated talus fracture. Evaluation of the post-test x-ray and CT images in conjunction with autopsy indicated similar fracture patterns between the whole-body tests and isolated foot-leg component tests used to develop the HIPCs. Heel contact forces and associated injury outcomes from the whole-body tests were compared with the severe calcaneus HIPC provided by Voo *et al.* (Fig. 1) [4]. Heel contact force associated with greater than 90% probability of severe calcaneus fracture consistently resulted in foot fracture, while heel contact forces associated with less than 30% probability of severe calcaneus fracture typically resulted in no fracture.

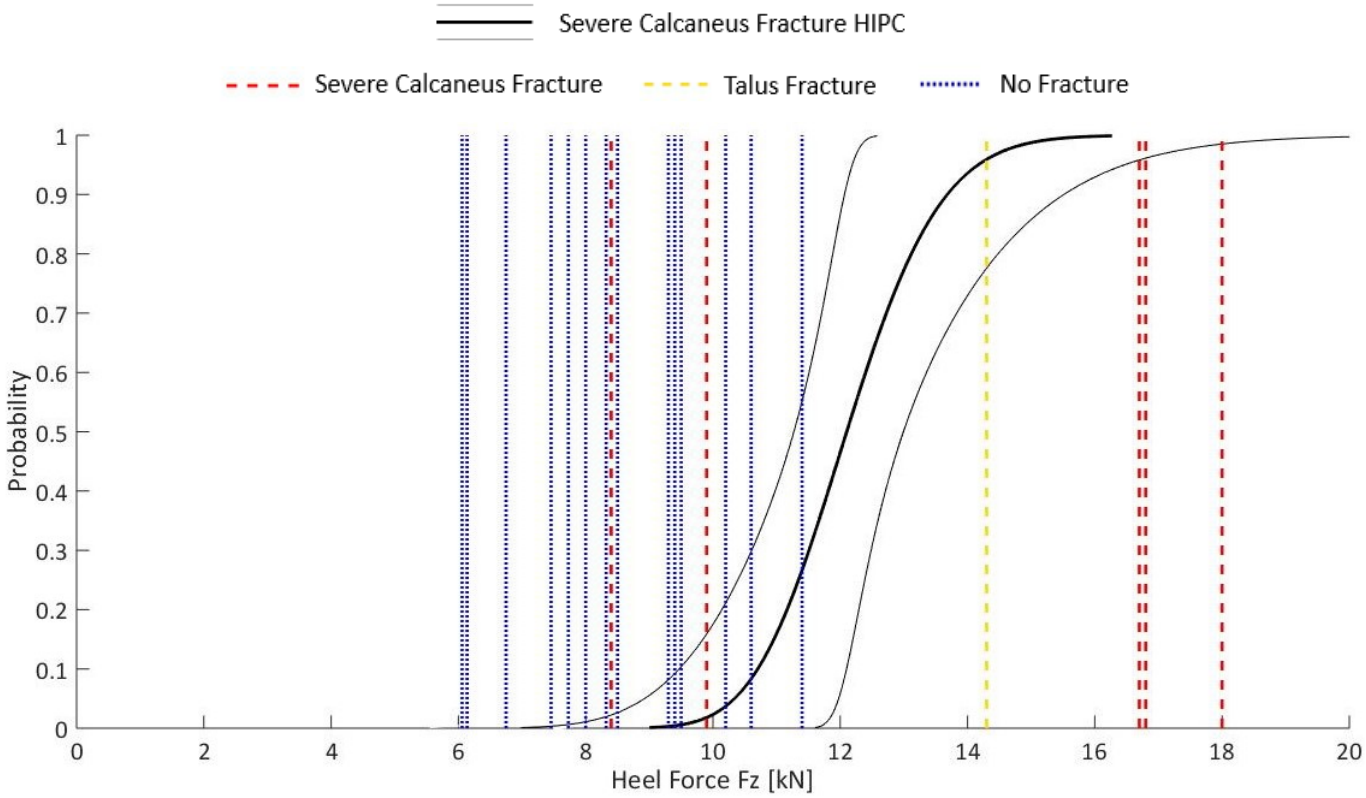

Fig. 1. Heel contact forces from whole-body tests compared to the severe calcaneus fracture HIPC.

IV. DISCUSSION

High-rate vertical loading to the feet and legs of whole-body PMHS resulted in fracture patterns similar to those created during testing of isolated foot-leg components, suggesting that a similar compression mechanism for calcaneus fracture was present in the component and whole-body tests. Prevalence of calcaneus fracture tended to increase with increased heel contact force in both whole-body and component tests and heel contact force reasonably predicted severe calcaneus fracture outcomes in whole-body tests. The results of this study indicate that heel contact force is an effective predictor of severe calcaneus fracture under high-rate vertical loading. Moreover, the HIPC provided by Voo *et al.* has been verified as predictive of severe calcaneus fracture to whole-body PMHS. Verification from the current study is limited to severe calcaneus fractures arising from vertical loading to the sole of the foot while the ankle is at 90 degrees. Future studies should include verification of the mild calcaneus fracture HIPC and evaluation of these HIPCs in a variety of foot positions, and ankle and knee postures.

V. REFERENCES

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