Determining Human Tibia Loads under Simulated Underbelly Blast Loading

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I. INTRODUCTION

Since World War II, anti-vehicle (AV) mines and Improvised Explosive Devices (IEDs) have become the greatest threat to military vehicles and their occupants [1]. When a vehicle triggers a mine, detonation of explosives generates superheated, high-pressure gas and ejects the surrounding soil at supersonic speed [2]. The gas expansion and soil ejecta under a vehicle can cause severe local structural deformations on the floor pan. This will generate significant axial load to the vehicular occupant resulting in lower limb injuries.

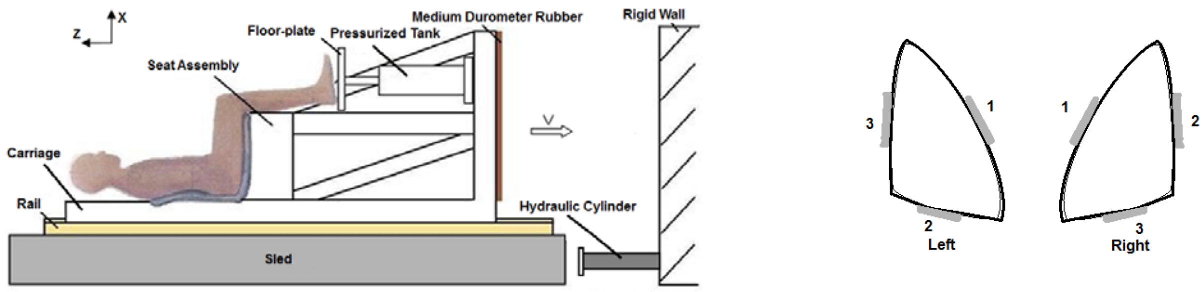
Several cadaver tests [3-4] have been conducted to study the foot-floor interaction at explosion-equivalent impact conditions. The foot-floor impact velocities in the published literature range from 7 to 12 m/s, which are much lower than reported values (up to 30 m/s) [2]. These experiments changed the integrity of lower limbs by either implanting tibia load cells or dissecting isolated tibia out of intact legs. As a result, injury patterns, associated injury mechanisms and injury criteria may be different from those obtained using intact limbs.

The objective of the current study was to conduct whole body impact tests in the caudal-cephalic direction to mimic real-world underbelly blast impacts. During the test, a new methodology was applied to estimate the compressive and bending loads on the intact tibia. Such information could be valuable to identify fracture mechanisms to the lower extremity under vertical loading generated by simulated blasts.

II. METHODS

A modified deceleration sled was used to generate biomechanically-relevant loads consistent with underbelly AV explosive devices. Figure 1 illustrates the orientation of the seat and the rigid barrier in relation to the direction of the sled movement. The setup consists of a horizontally-orientated seat assembly mounted on a carriage designed to slide with respect to the sled on a pair of aluminum rails. During the test, the Post Mortem Human Subject (PMHS) was secured to the seat via a four-point harness. The sled and seat were then accelerated simultaneously to a desired velocity, and the sled was stopped by two hydraulic cylinders located in front of the rigid barrier. The seat assembly continued sliding towards the rigid wall on two aluminum rails, and was stopped by a rigid wall with a layer of medium durometer rubbers in between. Changing the thickness of this layer controls the rate of caudal-cephalic acceleration pulses to the PMHS. Just prior to the seat-rigid barrier impact, a pressurized propane-air mixture was ignited inside the pressurized tank to accelerate the foot plate and produce axial loading to the lower extremities.

During the simulated underbelly blast loading, the tibia was subjected to a combined loading of force and moment along all directions. Experience with dummy testing and isolated cadaver legs with implanted six-axis load cells have shown reaction loads from all six components. However, major loadings were axial compression and bending along X and Y axes (refer to Figure 1a). Assuming each component is linearly correlated with the strain at a specific location, three strain gauges mounted along a tibia transaction (Figure 1b) will be sufficient to describe the applied loading across that section.



(a) (b)

Figure 1: A schematic diagram of the (a) experimental setup, and (b) locations of three strain gauges on tibia.

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Detailed procedures on calculation of the tibia load are described in Figure 2. First, it was assumed the Z-direction force and the moments along X and Y were the three major loading components in this loading scenario. Secondly, each strain gauge measurement was assumed to be the linear combination of these three loading components (the equation for the combined loading is shown in Figure 2). After each of the sled tests, the bone samples at the strain gauge region were dissected and calibrated by axial compression and bending tests along two different axes. Calibration results will solve the nine parameters (a_i, b_i, and c_i). Finally, tibia loads were estimated from the output of the strain gauges during the sled tests.

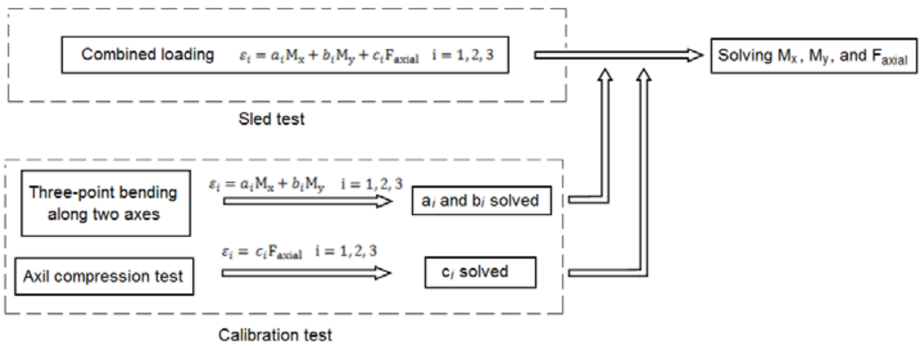

Figure 2: Procedures used to estimate tibia loads through calibration of post-test specimens

III. INITIAL FINDINGS

Two male PMHS were tested in this study. Only one impact per specimen was conducted. The impact velocity, tibia loading and autopsy results for the lower extremity are summarized in Table 1.

Table 1: Biomechanical responses and injuries on lower extremity

PMHS	V_{floor} (m/s)	Tibial Loading			Autopsy Result
		Mx (Nm)	My (Nm)	Faxial (kN)	
33999	13.4	Left: -230.6 Right: N/A	Left: 209.8 Right: N/A	Left: 4.63 Right: N/A	Malleolus fracture of right tibia
34124	26.3	Left: 77.1 Right: 165.9	Left: -155.2 Right: -170.7	Left: 5.83 Right: 7.68	Medial malleolus of right tibia fractured in multiple pieces; Right distal fibula fractured; Distal ends of both left tibia and fibula fractured with fragmentation

IV. DISCUSSION

Axial compression has been investigated as the injury mechanism of lower extremities since the 1990s [5-7]. In the current study, a large tibia bending moment along the X and Y axes was observed (see Table 1). The fracture pattern observed from the post-test autopsy also indicated that the tibia fracture was not solely due to axial compression. Given the fact that bone is anisotropic and has a higher fracture tolerance in compression than in tension, bending would be a better fracture mechanism than compression for long bones. The resultant moments calculated from the bending component along X and Y axes were over 200 Nm, which could be sufficient for fracture based on some criteria reported in the literature (184 Nm) [8]. The methodology introduced in this study provides feasibility to estimate the intact tibia load in axial compression and bending.

Due to the limited sample size, statistical analysis could not be applied to the experimental results, which was the major limitation of the current study. As a result, more tests are needed to establish the injury mechanism and associated tolerance for lower extremities during underbelly blast impact loading.

V. REFERENCES

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