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# The effect of impact duration on the axial fracture tolerance of the isolated tibia during automotive and military impacts

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## ABSTRACT

Axial impacts to the lower leg during debilitating events such as frontal automotive collisions and military underbody blasts can cause significant injuries to the tibia. Several studies have conducted axial impact tests to determine the injury limits of the lower leg, mostly focused on automotive intrusions, resulting in an established force criterion for injury assessments. Due to the viscoelastic properties of bone, it remains unclear whether results from automotive experiments can be applied to higher-rate military blasts. Twelve male isolated cadaveric tibias (from six pairs, mean age: 62 ± 8 years) were subjected to axial impact loads using a custom-built pneumatic impactor, with one specimen from each pair tested at velocity and impact durations representative of a military blast condition, and the contralateral under conditions representing an automotive collision. Impacts were applied in increasing levels of intensity (defined using energy levels) until fracture occurred. Fracture risk was influenced by projectile velocity, kinetic energy, impulse, and load rate, and there was a significant difference in peak force ($p = 0.023$), impulse ($p = 0.09$), and load rate ($p = 0.025$) between the automotive and military test conditions causing fracture. A 10% risk of fracture corresponded to an impact force of 9.0 kN for the automotive condition and 12.2 kN for the military condition. These results suggest that fracture tolerances developed in studies that simulate automotive impacts cannot be directly applied to military impacts of shorter duration. The number of factors identified to predict injury also suggests that fracture is not controlled by a single variable.

## 1. Introduction

Axial impacts to the lower leg, such as during frontal automotive collisions and military under body blasts (UBBs) in combat zones, can cause significant injuries (Ramasamy et al., 2011). Although damage to this region is typically not life threatening, it can result in disability or impairment, which leads to emotional distress to the injured person and decreased workplace productivity (Dischinger et al., 2004; McKay and Bir, 2009; Owen and Lowne, 2001). To reduce these negative outcomes and design suitable protective measures, the injury tolerance of the lower leg must be well understood.

Injuries to this region of the body during frontal automotive collisions and UBBs are caused by an analogous injury mechanism, whereby axial loads are transferred along the long axis of the lower leg due to floor intrusion or interaction with the vehicle's pedals (Gallenberger et al., 2013). However, the magnitude of velocity and duration of the impact vary between the two scenarios. Automotive floor pan impacts typically have velocities between 2 and 6 m/s (Crandall et al., 1998; McKay and Bir, 2009), and impacts lasting between 15 and 45 ms (McKay and Bir, 2009). Meanwhile, floor plate velocities during UBBs have been reported to exceed 12 m/s (Wang et al., 2001), with load durations less than 10 ms (North Atlantic Treaty Organization HFM-090 Task Group 25, 2007). With the introduction of novel protective devices such as energy attenuating floor mats (Quenneville and Dunning, 2011), the durations of these impacts may also vary outside of previously reported ranges.

Previous studies have conducted axial impact tests to determine the injury limits of the cadaveric lower leg (*e.g.*, Bailey et al., 2015; Gallenberger et al., 2013; Quenneville et al., 2011), with the majority of this research being carried out with an automotive focus. These studies suggested a peak axial force between 2.4 kN (Seipel et al., 2001) and 7.9 kN (Quenneville et al., 2011) is associated with a 10% risk of fracture; however, these force values give little indication of impact duration and correspondingly, impulse. To date, no known study has used reported impact duration values for automotive and military impacts to directly study its effect on the lower leg's fracture tolerance. Due to the viscoelastic properties of bone, it remains unclear whether results from automotive experiments can be successfully applied to

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higher loading rate military blasts (Bailey et al., 2015). It is possible that varying the duration of loading may have an effect on the risk of injury of the lower leg. Therefore, the purpose of this study was to investigate the effect of impact duration and impulse on the fracture tolerance of the tibia during automotive and military impacts.

## 2. Materials and methods

### 2.1. Specimen preparation

Twelve (*i.e.,* six pairs) male fresh-frozen isolated cadaveric tibias (age 62 ± 8 years, no previous history of ankle trauma or surgery) stripped of all soft tissues were obtained for impact testing. Male specimens were chosen to be representative of the military population being studied as one condition in this study. Isolated tibias were chosen to eliminate the number of degrees of freedom associated with the numerous joints and tissues in intact limbs, for better control during the experimental procedure, and for the direct investigation of the effect of impact duration and loading rate on bone fracture tolerance, with the expectation that observations from this work could be extrapolated to other long bones of the body that undergo similar loading mechanisms.

The proximal end of each tibia was potted in dental cement to provide a consistent method of support during testing and to ensure proper axial alignment. A custom-designed frame that supported each tibia vertically (proximal end down, in a section of 4” diameter PVC pipe), while allowing adjustment in its alignment in all directions using threaded rods was used for potting. Consistent alignment was ensured using laser levels, with the laser being projected along the anterior ridge of the tibia at mid-shaft in the frontal plane, and aligned with the center of the medial malleolus in the medial plane. The bone was embedded in cement to the full depth of the PVC pipe (3”) and allowed to cure. The PVC pot was then flipped and the void in the cement beneath the specimen was filled in and levelled with more cement. Each potted specimen was weighed so the required ballast mass could be added to the mounting frame before impact testing to ensure consistent post-impact kinematic behaviour across all tests. All specimens were thawed for a minimum of four hours before testing.

### 2.2. Testing apparatus and instrumentation

Impacts were applied via an apparatus that uses a pneumatic system to propel a projectile of variable mass to strike a specimen within a test chamber (Fig. 1a). The pressure released from the pneumatic tank caused the projectile to travel along an acceleration tube before impacting the specimen via a impact plate covered with extra firm density closed cell silicone sponge. The test specimen hung from adjustable chains on a rail and bearing system that allowed the position and angle of the specimen to be easily altered as well as free motion following the impact. The specimen was positioned using a level measured at mid-diaphysis so that the applied load was in line with the long axis of the tibia, producing a primarily axial load. For inertial purposes, ballast mass was added to the mounting frame to bring the total mass to 12.9 kg, which is representative of the mass of the 50th percentile male upper leg, lower leg, and foot (Huston, 2009).

Efforts were made to ensure the load from the projectile was applied to the articular surface of the distal tibia in a realistic manner. Artificial tali were created for both the right and left sided specimens using high density acrylonitrile butadiene styrene (ABS) rapid prototyping based on Computed Tomography (CT) scans taken of male lower legs, to minimize any stress concentrations when transferring the load and withstand the high impact loads (Fig. 1b).

A six-axis load cell (IF-625, Humanetics, Plymouth, MI, USA) was used to measure the forces and moments applied to the specimens. The velocity of the projectile was calculated using two photoelectric sensors (PZ-V31P, Keyence Corporation, Osaka, Japan) mounted to the end of the acceleration tube, adjacent to one other. All signals from the instrumentation were collected using a data acquisition system (PXIe-1082, National Instruments, Austin, TX, USA) and custom-written LabVIEW (National Instruments, Austin, TX, USA) program at a sampling rate of 50 kHz.

### 2.3. Experimental protocol

Two different experimental conditions were simulated: a higher-rate military underbody blast and a lower-rate automotive crash. The UBB condition had a target velocity of 12 m/s (Wang, 2001) and a target impact duration of 5 ms (North Atlantic Treaty Organization HFM-090 Task Group 25, 2007). The testing condition representative of a frontal automotive crash was constrained to target a lower velocity of 6 m/s (McKay and Bir, 2009) but longer impact duration of 20 ms (North Atlantic Treaty Organization HFM-090 Task Group 25, 2007). One specimen from each pair was tested at the lower-rate condition, while the contralateral was impacted at the higher-rate condition, with right-left selection randomized. In order to keep the velocity and duration values constant throughout the trials, mass was added to the projectile to increase the intensity level of each successive impact until fracture occurred, defined as the distal end of the tibia being separated into at least two distinct sections. The duration of the impact was controlled using silicone sponge attached to the impact plate on the projectile side of the plate. An iterative approach was used to determine the sponge thicknesses required to achieve the required impact durations prior to testing, and a thickness of 50 mm was selected to control the duration

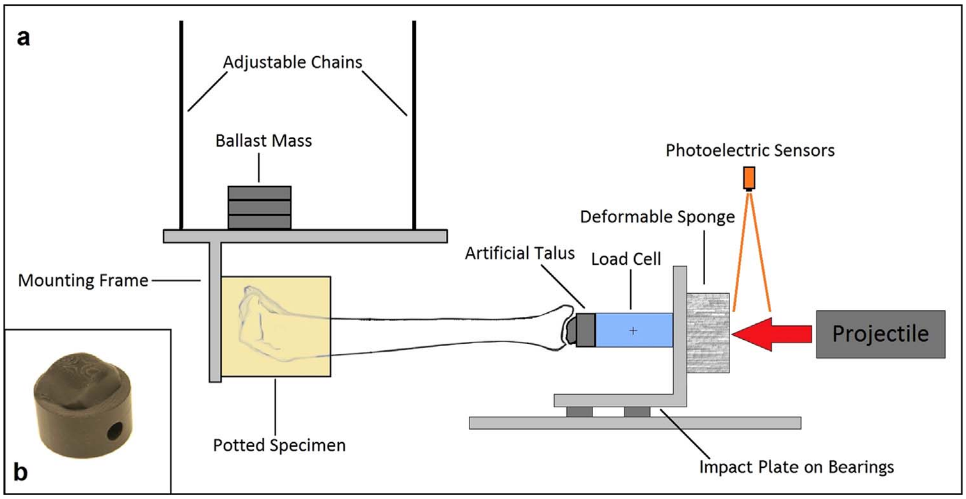

**Fig. 1.** Experimental Test Setup (a) Schematic of the experimental setup showing the specimen and instrumentation; (b) the artificial talus used to transmit the impact loads to the specimen.