The Effect of Impulse on the Axial Fracture Tolerance of the Isolated Tibia During Automotive and Military Impacts

Alberto Martinez[1], Avery Chakravarty[1], Cheryl E. Quenneville[1,2]

[1]Department of Mechanical Engineering, McMaster University, Hamilton, Ontario, Canada
[2]School of Biomedical Engineering, McMaster University, Hamilton, Ontario, Canada

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. In this study, the effect of impulse and loading rate on the fracture tolerance of the tibia was investigated. Eight male isolated cadaveric tibia specimens (from six pairs, mean age: 62 ± 8 years) were subjected to axial impact loads using a custom-built pneumatic impactor. Foam of varying levels of compliance was placed in line with the impacts to control the impact durations. One specimen from each pair was tested for the military blast condition and the contralateral for the automotive condition, with right-left selection randomized. Impacts were applied in increasing levels of intensity (defined using energy levels) until fracture occurred. Impact levels were selected to limit the number of strikes to each specimen (to minimize any accumulated damage). Paired t-tests were used to determine whether there was a statistically significant difference between the two test conditions for several of the impact parameters. It was found that there was a statistically significant difference in peak force ($p = 0.022$), acceleration ($p = 0.04$), and kinetic energy ($p = 0.082$) between the automotive and military test conditions, but not impulse ($p = 0.216$). The model determined to be most successful for predicting fracture by a best subsets regression analysis included projectile velocity, peak force, kinetic energy, impulse, and impact plate acceleration. Ongoing testing will increase the sample size of the study and allow development of a rate-dependent injury criterion.

INTRODUCTION

Axial impacts to the lower leg, such as during frontal automotive collisions and under body blasts in military combat zones, can cause significant injuries. 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, decrease in workplace productivity, and long-term healthcare costs. In order 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 AV blast are caused by an analogous injury mechanism, whereby axial loads are transferred along the long axis of the lower leg due to floor intrusion (Figure 1a) or interaction with the vehicle's pedals (Figure 1b) (Gallenberger, 2013). However, the magnitude of velocity and duration of the impact vary between the two scenarios. Automotive floor pan impacts typically have velocities ranging from 2.0 to 6.0 m/s (Crandall, 1998; McKay, 2009), and impacts lasting between 15 and 45 ms (McKay, 2009). Meanwhile, floor plate velocities during AV blasts impacts have been reported to exceed 12 m/s (Wang, 2001), with load durations less than 10 ms (North Atlantic Treaty Organization TR-HFM-090, 2007).

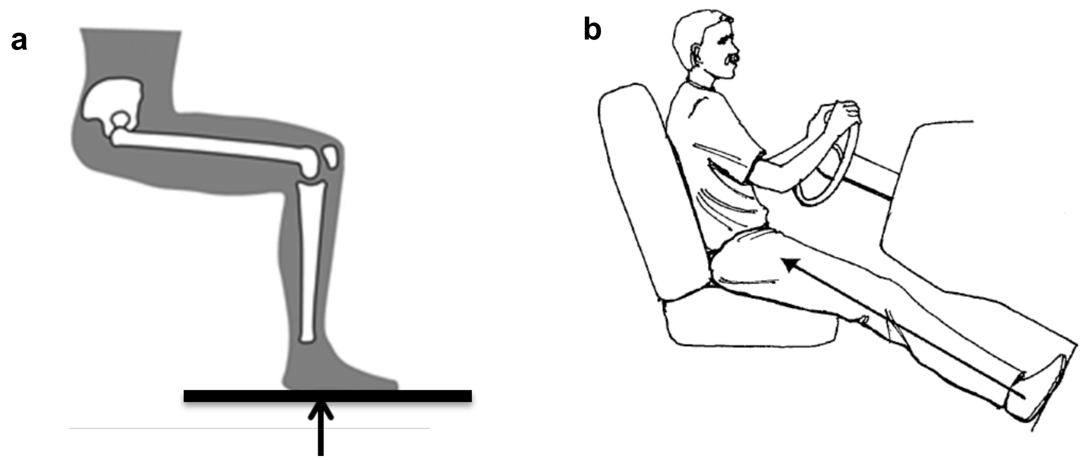

Figure 1: **a)** Impact loading of the lower leg due to military vehicle underbelly blast; **b)** transfer of an axial load from an automotive floor pan to the lower leg (Whiting, 1998).

Previous studies have conducted axial impact tests to determine the injury limits of the cadaveric lower leg (e.g., Quenneville, 2011; Gallenberger, 2013; Bailey, 2015), with the majority of this research being carried out with an automotive focus. These studies suggested a peak axial force between 5.5 kN (Seipel, 2001) and 8.3 kN (Funk, 2002) is associated with a 50% risk of fracture; however, these force values give no indication of impact duration (and correspondingly, impulse). To date, no known study has varied the duration of impact to determine its effects. Due to the viscoelastic properties of bone, it remains unclear whether results from automotive experiments can be successfully applied to higher loading rate military blasts. It is possible that varying the duration of loading may have an effect on the risk of injury of the tibia. Therefore, the purpose of this study was to investigate the effect of impact duration, and therefore impulse, on the fracture tolerance of the tibia during automotive and military impacts.

METHODS

Specimen Preparation

Twelve (*i.e.,* six pairs) of male fresh-frozen isolated cadaveric tibias (age 62 ± 8 years) 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. All specimens were thawed for a minimum of four hours before testing.

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. The bones were potted using a custom-designed frame that is capable of supporting the specimen and adjusting its alignment using threaded rods (Figure 2). The tibias were suspended vertically within a section of PVC pipe of 4" diameter and 3" length. They were then aligned in the pot using laser levels, with the laser being aligned with 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 and allowed to cure.

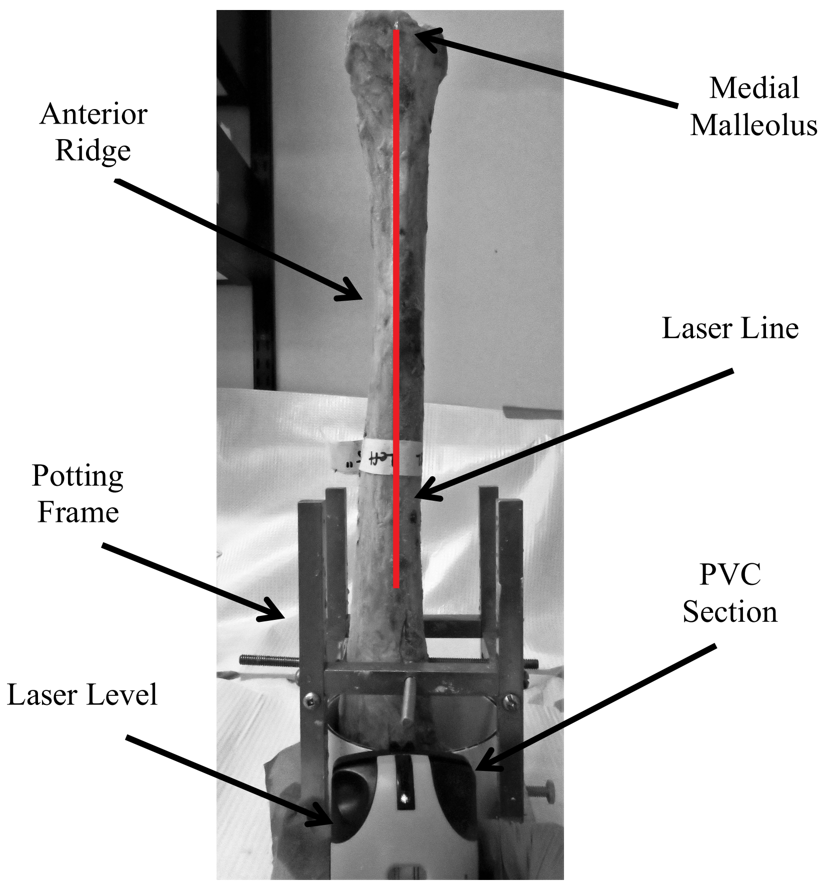

Figure 2: Specimen potting and alignment. Tibias were supported using the potting frame, and aligned based on anatomical landmarks using a laser level, after which they were potted in PVC pipe using dental cement.

Testing Apparatus and Instrumentation

Impacts were applied to the specimens using a pneumatic apparatus that propels a projectile of variable mass along an acceleration tube before impacting the specimen via a footplate covered with extra firm density closed cell silicone foam (Figure 3a). An artificial talus was created to transmit the load in a realistic manner from the footplate to the specimen (Figure 3b), and was rapid prototyped based on a CT scan taken of a male lower leg specimen. The artificial talus is mounted to a load cell (see below), and transmits the load to the test specimen, which hangs from adjustable chains on a rail and bearing system, allowing the position and angle of the specimen to be easily set. Specimens were held in line with the direction of impact, in order to induce primarily axial load and ballasted to a mass of 12.9 kg, which is representative of the mass of the leg of the 50th percentile male (Huston, 2009).

A six-axis load cell (IF-625, Humanetics, Plymouth, MI, USA) was used to measure the force and moments applied to the distal end of the bone. A uniaxial accelerometer (MMA1200KEG, Freescale Semiconductor, Ottawa, ON, Canada) with a range of ± 250 g was attached to the impact plate to quantify the input acceleration. 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 each other. The 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.

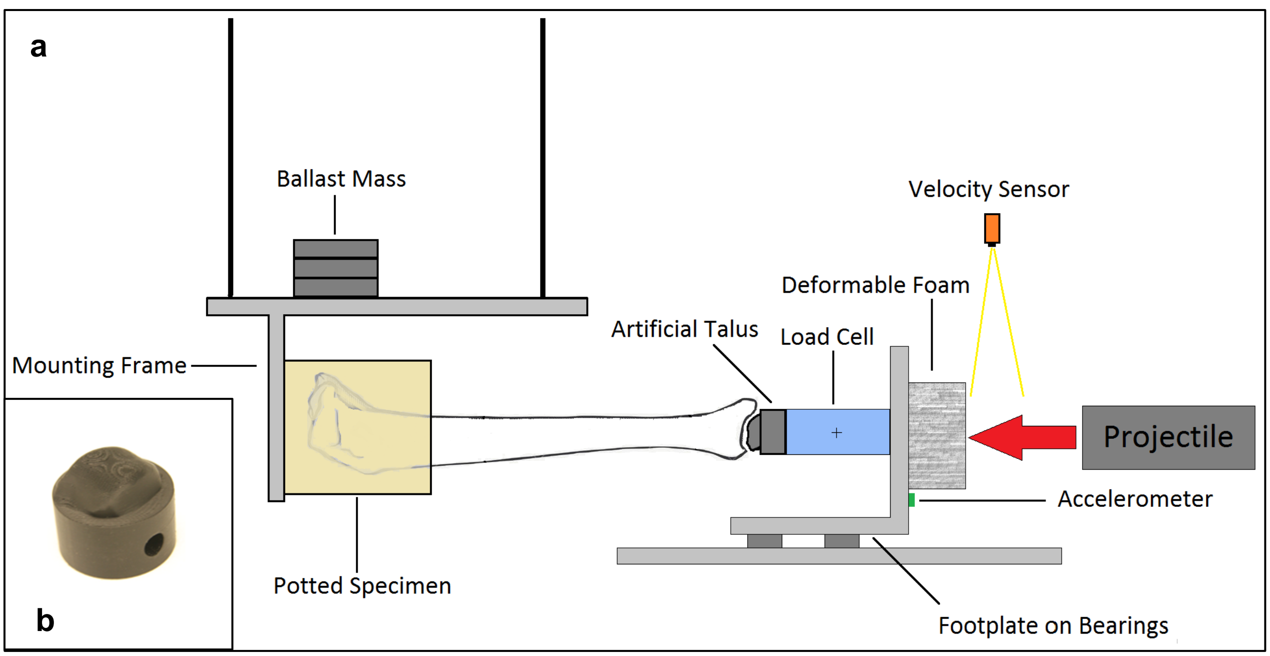

Figure 3: **a)** Schematic of the experimental setup showing the specimen and instrumentation; **b)** the artificial talus used to transmit the impact loads to the specimen.

Experimental Protocol

Two different experimental conditions were simulated, an AV blast and an automotive crash. The AV blast condition had a target velocity of 12 m/s (Wang, 2001) and impact duration of 5 ms (North Atlantic Treaty Organization TR-HFM-090, 2007). The frontal automotive crash condition was constrained to target a lower velocity of 6 m/s (McKay, 2009) but longer impact duration of 20 ms (North Atlantic Treaty Organization TR-HFM-090, 2007). One specimen for each pair was tested at the automotive condition, while the contralateral was impacted at the military blast 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 the silicone sponge of varying thicknesses attached to the impact plate. This material was chosen to extend the duration of the impact due to its firm density and ability to withstand multiple impacts without damage.

A best subset regression analysis was performed on data collected during the impact tests to identify the factors that contribute to injury risk. Donor age, projectile mass, projectile velocity, impact force, impact duration, projectile kinetic energy, projectile momentum, impulse (defined as the integral of the force-time curve), and impact plate acceleration were considered, with the response set to 1 for fracture tests and 0 for non-fracture tests. Paired t-tests were also used to determine whether there was a statistically significant difference between the two test conditions for the various factors. A significance level of $\alpha = 0.1$ was used due to the small number of specimens available for statistical analysis.

RESULTS

Nine of the specimens have been tested to date, while ongoing testing is still needed for three of the automotive specimens. In each test, intra-articular damage occurred at the distal end of the tibia (Figure 4). It took an average of 3.7 (± 1.8) impacts to achieve fracture in the specimens. The military tests had an average velocity of 11.2 (± 0.4) m/s and average impact duration of 5.3 (± 0.5) ms, compared to a velocity of 5.5 (± 0.9) m/s and impact duration of 20.5 (± 4.6) ms for the automotive condition.

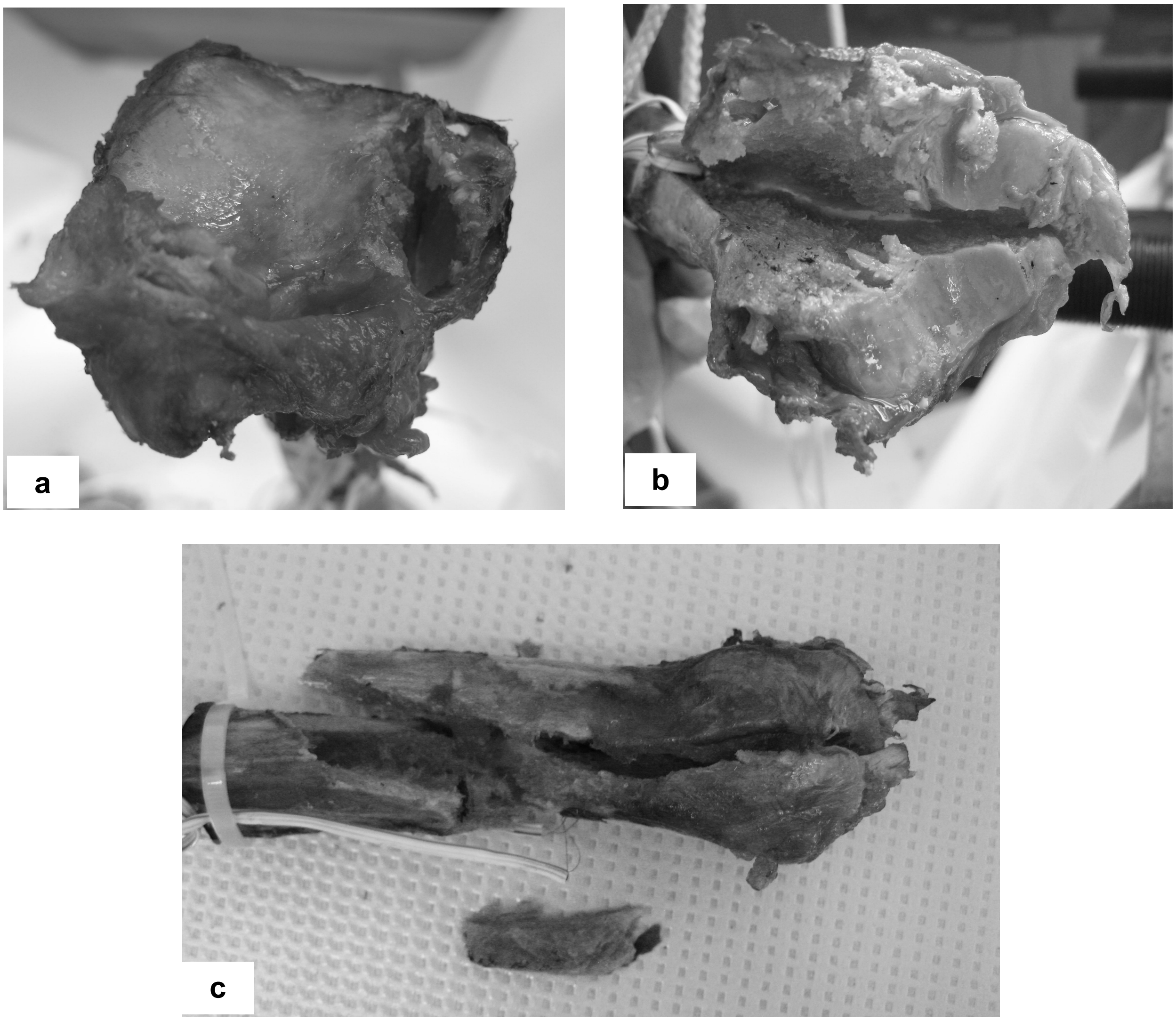

Figure 4: Typical fracture patterns at the distal end of the tibia for specimens **a)** 1536R, **b)** 1541R, and **c)** 1567R.

Figure 5 shows the fracture force-time curves for a representative specimen for both the automotive and military conditions. The military test condition consistently achieved larger peak force values than the automotive test condition, but the impact duration was much shorter. Even though the peak force was less for the automotive condition, the impulse values were greater as a result of the longer impact duration (Table 1). For most of the specimens, the greatest force occurred at the second-last impact, prior to the impact that caused fracture. Table 1 includes the results from the final impact that caused fracture and the impact just previous to it, denoted as the pre-fracture impact. Specimens 1494L and 1538L do not have data for a pre-fracture test since these specimens fractured at the first impact that was delivered. The greatest forces and impulses consistently occurred in the pre-fracture tests, while the greatest projectile mass and kinetic energy corresponded to the final fracture tests. As such, peak values for each factor were used for the paired t-tests.

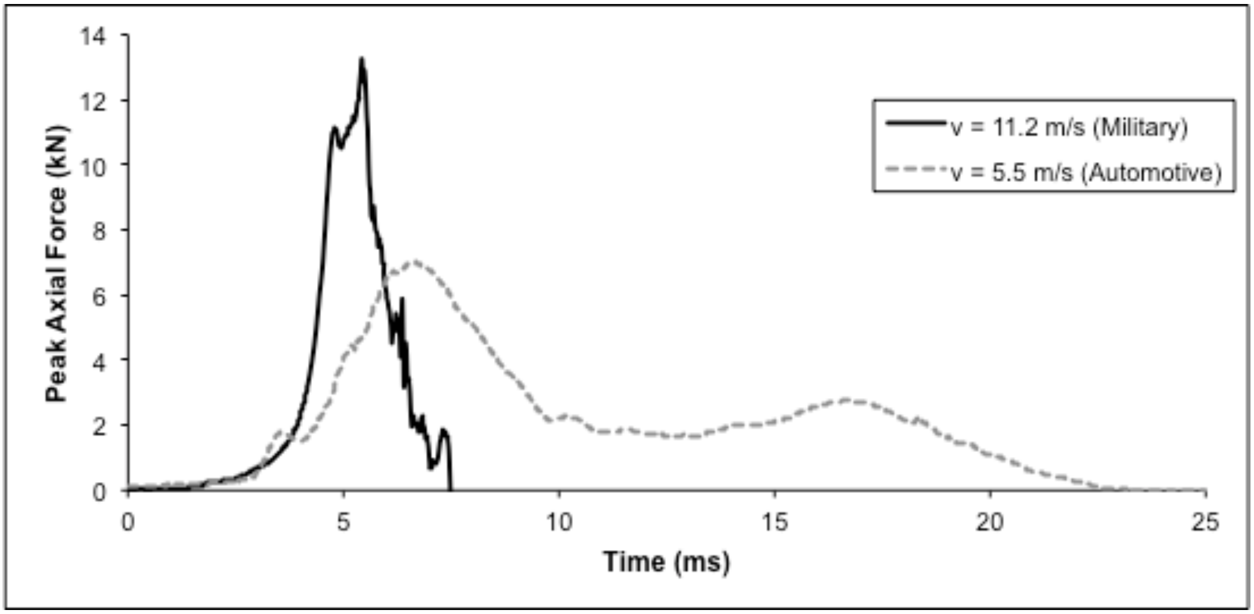

Figure 5: Force-time curves for the fracture impacts of specimens 1536. The military condition had a larger peak force but shorter duration (13.5 kN, 5.3 ms) than the automotive condition (10.2 kN, 20.5 ms). Impulse was calculated as the integral of each force-time curve.

Table 1: Results for the **a)** automotive impact condition and **b)** military blast including both the pre-fracture impact (with the highest force) and the fracture impact. The highlighted values represent the greatest average values for each factor, with peak forces and impulses occurring in the pre-fracture test and peak projectile masses and kinetic energies occurring in the fracture test

a) **Automotive Impact Condition, v_{avg} =5.5 m/s, Δt_{avg} = 20.5 ms**

	Pre-Fracture				Fracture			
Specimen	**Projectile Mass (kg)**	**Force (N)**	**Kinetic Energy (J)**	**Impulse (Ns)**	**Projectile Mass (kg)**	**Force (N)**	**Kinetic Energy (J)**	**Impulse (Ns)**
1494R	27.8	10672	435	53.8	31.6	8071	381	32.7
1536R	25.0	10826	362	52	61.3	7049	381	50.8
1538L	-	-	-	-	21	9063	449	26.1
Average (±S.D.)	**26.4 (2.0)**	**10749 (109)**	**398.3 (51.5)**	**52.9 (1.3)**	**28.1 (6.1)**	**8061 (1007)**	**404 (39)**	**36.5 (12.8)**

b)	Military Blast Condition, v_{avg} = 11.2 m/s, Δt_{avg} = 5 ms							
	Pre-Fracture				Fracture			
Specimen	**Projectile Mass (kg)**	**Force (N)**	**Kinetic Energy (J)**	**Impulse (Ns)**	**Projectile Mass (kg)**	**Force (N)**	**Kinetic Energy (J)**	**Impulse (Ns)**
1494L	-	-	-	-	6.9	13275	443	22.1
1536L	7.6	14258	594	30.3	8.3	13255	548	22.9
1538R	6.9	13500	443	27.3	8.3	7271	533	14.9
1541R	6.5	11812	417	27.3	6.5	10171	429	18.8
1567R	6.3	10453	405	27.3	6.9	13311	443	18.2
1600L	3.6	14542	416	24.4	7.6	12575	408	21.6
Average (±S.D.)	**6.3 (0.5)**	**12913 (1737)**	**455 (79)**	**27.3 (2.1)**	**7.4 (0.8)**	**11643 (2457)**	**467 (39)**	**19.8 (3.0)**

Statistical Analysis

Based on the value of the adjusted R-squared from the best subsets regression analysis, the best model for predicting fracture included projectile velocity, peak force, kinetic energy, impulse, and impact plate acceleration (adjusted R^2 = 44.2).

It was found that there was a statistically significant difference in peak force (p = 0.022) (Figure 6), acceleration (p = 0.04), and kinetic energy (p = 0.082) (Figure 7) between the automotive and military test conditions, but not impulse (p = 0.216) (Figure 8). Three of the specimens do not have data for the automotive condition, since these tibias are yet to be tested.

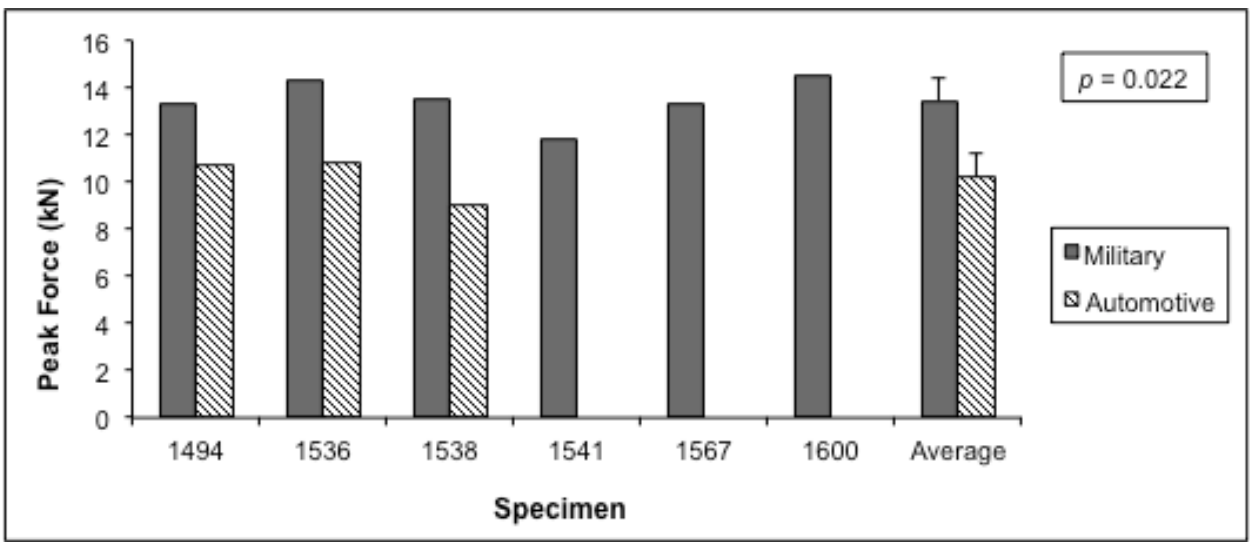

Figure 6: Peak force values for each specimen. For the donors that had specimens tested in both the automotive and military condition, the peak force was lower in the automotive case. The peak force values were averaged across all specimens and standard deviations are shown with error bars.

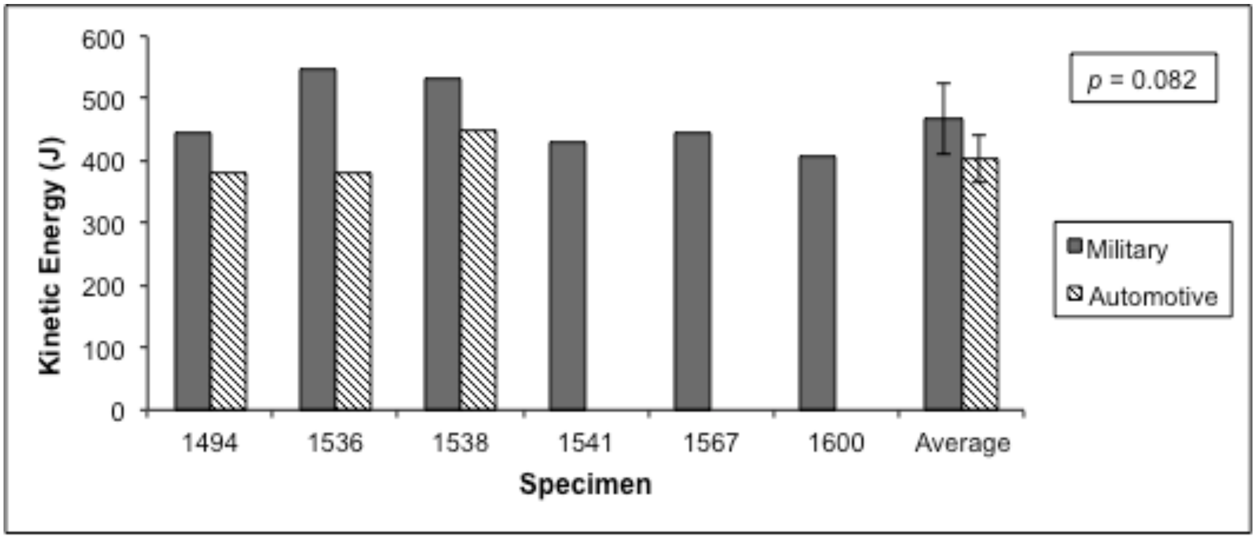

Figure 7: Peak kinetic energy values presented for each specimen for both the automotive and military condition and averaged across all specimens and standard deviations are shown with error bars.

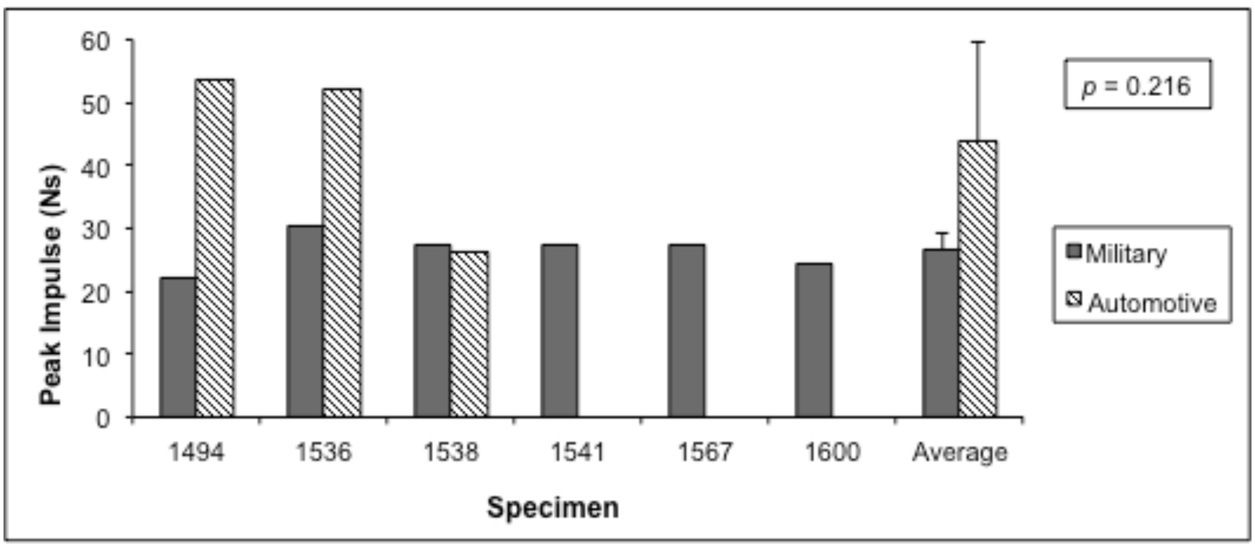

Figure 8: Peak impulse values presented for each specimen. The peak impulse values were averaged across all specimens and standard deviations are shown with error bars.

DISCUSSION

This study examined the fracture tolerance of the tibia and the effect of impulse during automotive and military axial impacts. While there have been several studies that have conducted experimental testing on the lower leg (e.g., Quenneville, 2011; Yoganandan, 2014; Bailey, 2015), the effect of varying impact durations has not been seen previously in the literature. Since most of the prior research has focused on automotive injuries, understanding the effect of impulse is critical in determining whether automotive results can be successfully applied to military blast scenarios.

The results from impact testing showed that the greatest force and impulse values occurred prior to the impact test. During this pre-fracture test, a crack usually became visible at the articular surface of the tibia, suggesting that forces were very close to the failure level. The pre-fracture test had the greatest forces and impulses due to the damage that occurs during the fracture test, which provided less resistance and absorbed a portion of the energy. The peak force was used for statistical analysis since it is most indicative of the tolerance of the lower leg, since the body is not typically subjected to repeated impacts of this magnitude. Based on the three pairs of specimens that were tested, it was found that specimens tested in the automotive condition with longer impact durations require smaller axial forces to achieve fracture when compared to the shorter duration military condition. The data suggest that there is no difference in the impulse required to generate fracture between the two test conditions, and therefore this may be a good indicator of fracture risk, regarding of the duration of impact. The best subset regression analysis revealed that several factors including projectile velocity, peak force, kinetic energy, impulse, and impact plate acceleration provide the most accurate method of injury prediction. The number of factors identified by the regression analysis suggests that fracture is not controlled by a single variable, but a combination of several. There is also a degree of interdependence that exists between these factors, as factors such as force, energy, and acceleration are dependent on the velocity. While several of these factors are not often measured experimentally in fracture tests (*i.e.,* impulse and acceleration), the data suggest that their measurement and consideration may lead to more accurate injury prediction.

While no other work has investigated the effect of impact duration on the fracture tolerance of the tibia, the peak fracture force values of 10.2 – 13.5 kN lie within the range of expected values reported in a previous study that conducted impact testing on isolated tibia specimens (Quenneville, 2011). Kinetic energy was also identified as a significant factor that influences failure in that study, which suggests that kinetic energy should be considered a contributing factor to injury risk, along with force. Impulse values, however, are typically not reported in other studies, but the results of this work suggest that this could be of benefit when defining the fracture tolerance of the tibia, and should be included in future studies to allow for comparison.

There are several limitations of this work that must be acknowledged. The specimens tested had all soft tissue and the fibula, foot and ankle removed, as well as muscle tension in the specimens was not simulated. However, efforts were made to simulate the inertial effects of the soft tissue with the ballast mass. The lack of foot and ankle present in the specimens allowed controlled investigation of the effect of loading rate on bone fracture, and these results may be extrapolated to fractures of the bones of the foot and ankle. Another limitation was the number of impacts that each specimen was subjected to and any damage that may have developed during repeated testing. However, one specimen fractured at the very first impact delivered and exhibited fracture forces within the range of the other specimens, suggesting that repeated testing did not dramatically affect the range of force tolerances identified herein. Finally, the small sample size of this study must be acknowledged. Ongoing testing will include the remaining specimens in the automotive test condition, for a total of six pairs of tibias for the entire study.

A Weibull survivability curve will be developed once testing has been completed on all specimens. Additionally, the cadaveric risk functions that are developed must be transferred into functional values that can be used by industry. In order to do so, the Hybrid III and MIL-LX anthropomorphic test device (ATD) lower legs will be tested under similar impact conditions as the cadaveric specimens. The ability of the ATD to accurately predict the injury risk for humans subjected to the same input conditions is crucial when developing and evaluating appropriate protective systems.

CONCLUSIONS

By conducting impact testing on the tibia simulating both frontal automotive loads and military blast impacts, the effect of the impact duration on the injury tolerance of the tibia was identified. To date, no other work has been conducted that compared the velocities and impact durations reported in literature for both of these scenarios. Based on the specimens tested it was determined that Based on the specimens tested, it was determined that projectile velocity, peak force, kinetic energy, impulse, and impact plate acceleration were identified as the factors that best predict the fracture tolerance of the tibia. The number of factors identified to predict injury suggests that fracture is not controlled by a single variable, but a combination of several, which may require additional instrumentation to be added to ATDs in the future. Automotive impacts with longer durations required smaller forces to produce fracture than higher-rate impacts with shorter durations. Similarly, kinetic energy values for automotive impacts were smaller when compared to the military condition. This suggests that kinetic energy should be considered as a factor used to predict injury, along with force. These data will be useful for developing a novel comprehensive criterion that accounts for varying levels of combined loading.

ACKNOWLEDGEMENTS

This research is funded by the Canada Foundation for Innovation (CFI), the Natural Sciences and Engineering Research Council of Canada (NSERC), the Ontario Research Fund (ORF), and McMaster University. We would like to thank the other members of the McMaster Injury Biomechanics Laboratory for their support and the donors for their kind contributions.

REFERENCES

BAILEY, A. M., MCMURRY, T. L., POPLIN, G. S., SALZAR, R. S., & CRANDALL, J. R. (2015). Survival model for foot and leg high rate axial impact injury data. Traffic injury prevention, 16(sup2), S96-S102.

CRANDALL, J. R., MARTIN, P. G., SIEVEKA, E. M., PILKEY, W. D., DISCHINGER, P. C., BURGESS, A. R., O'QUINN, T.D., & SCHMIDHAUSER, C. B. (1998). Lower limb response and injury in frontal crashes. Accident Analysis and Prevention, 30(5), 667–677.

FUNK, J. R., CRANDALL, J. R., TOURRET, L. J., MACMAHON, C. B., BASS, C. R., PATRIE, J. T., KHAEWPONG, N., & EPPINGER, R. H. (2002). The axial injury tolerance of the human foot/ankle complex and the effect of Achilles tension. Journal of Biomechanical Engineering, 124(6), 750–757.

GALLENBERGER, K., YOGANANDAN, N., & PINTAR, F. A. (2013). Biomechanics of foot/ankle trauma with variable energy impacts. Annals of Advances in Automotive Medicine. Scientific Conference, 57, 123–32.

HUSTON, R. L. (2009). Principles of Biomechanics (1st ed.). Boca Raton, FL: CRC Press.

JACOB, N., AMIN, A., GIOTAKIS, N., NARAYAN, B., NAYAGAM, S., & TROMPETER, A. J. (2015). Management of high-energy tibial pilon fractures. Strategies in Trauma and Limb Reconstruction, 10(3), 137–147.

MCKAY, B. J., & BIR, C. A. (2009). Lower extremity injury criteria for evaluating military vehicle occupant injury in underbelly blast events. Stapp Car Crash Journal, 53(November), 229–249.

NORTH ATLANTIC TREATY ORGANIZATION TR-HFM-090. (2007). Test methodology for protection of vehicle occupants against anti-vehicular landmine effects. Final Report of the Human Factors and Medicine Task Group 090 (HFM-090).

QUENNEVILLE, C. E., MCLACHLIN, S. D., GREELEY, G. S., & DUNNING, C. E. (2011). Injury tolerance criteria for short-duration axial impulse loading of the isolated tibia. The Journal of Trauma: Injury, Infection, and Critical Careauma, 70(1), E13–E18.

SEIPEL, R. C., PINTAR, F. A., YOGANANDAN, N., & BOYNTON, M. D. (2001). Biomechanics of calcaneal fractures: A model for the motor vehicle. Clinical Orthopaedics & Related Research, (388), 218–224.

WANG, J., BIRD, R., SWINTON, B., & KRSTIC, A. (2001). Protection of lower limbs against floor impact in army vehicles experiencing landmine explosion. Journal of Battlefield Technology, 4(3), 8–12.

WHITING, W.C., & ZERNICKE, R.F. (1998). Ch. 6: Lower-Extremity Injuries, in Biomechanics of Musculoskeletal Injury. Human Kinetics.

YOGANANDAN, N., ARUN, M. W., PINTAR, F. A., & SZABO, A. (2014). Optimized lower leg injury probability curves from postmortem human subject tests under axial impacts. Traffic injury prevention, 15(sup1), S151-S156.