The response of the MiL-Lx leg fitted with combat boots under impact loading

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Abstract

Anti-Vehicular Landmines (AVLs) or under-belly Improvised Explosive Devices (IEDs) or even a side-attack IEDs are found to be some of the major threat for military vehicles and their occupants. The lower extremities of the occupants are very prone to the injuries more especially during underbelly detonation of the AVL or IED due to their spatial proximity to the rapid deforming floor. Lower limb surrogate legs, such as a Hybrid III or Military Lower Extremity (MiL-Lx) are used to quantify the impulse loading on the lower extremity when subjected to the rapid deforming floor. Military boots could be used by the occupants to mitigate the blast loading impact on the lower extremities. This work present the response of the MiL-Lx leg fitted with two different combat boots (Meindl and Lowa) and exposed to typical blast loading conditions. The purpose of the work was to evaluate the potential load mitigation effects of the two boots using the MiL-Lx leg. The blast loading conditions were simulated using the modified lower limb impactor at several loading velocities spanning from 2.7-10.2 m/s. The MiL-Lx leg was instrumented with triaxial load cells located at the upper and lower tibia. The results shows that both combat boots attenuate the peak force only at the lower tibia while showing slight increase of the peak force at the upper tibia. Within the lower loading severities, the Meindl desert combat boot shows a better peak force attenuation than the Lowa desert combat boot at the upper tibia. Both boots shows a delay in time to peak force at both upper and lower tibia. The Meindl boot shows a longer delay in time to peak force than the Lowa desert combat boot. Both boots shows an increase in impulse determined at the upper and lower tibia and across the loading severities. The increase in impulse is attributed to the presence of the boot materials and the thicker boot showed a higher increase.

Keywords: *MiL-Lx, Blast Impact, Military combat boots, Anti-Vehicular Landmine*

1. Introduction

The lower extremities of occupants of the military vehicle experience high impulse loading due to rapid deformation of the floor following detonation of an explosive threat such as an Anti-Vehicular Landmine (AVL) or under-belly Improvised Explosive Device (IED) or even a side-attack IED. This impact causes significant soft tissue and/or bony injuries, leading to a long recovery, medical complications and may require limb amputation if not mitigated [1]. The military boots which the occupants wear in these vehicles could attenuate the effect of the resulting occupant load and reduce injury probability. To quantify the effect of high impulse loading on the vehicle occupants instrumented lower limb surrogate legs, such as a Hybrid III (HIII) or Military Lower Extremity (MiL-Lx), are used in conjunction with a specified Anthropomorphic Test Device (ATD) [2]. Typical military vehicle instrumented with the ATD and surrogate legs is subjected to the underbelly detonation of 6-10 kg Trinitrotoluene [3].The surrogate leg captures test information such as the transferred lower leg load, displacement and acceleration of the lower limb. These surrogate legs are also commonly used in laboratories and scaled field tests to evaluate mitigation concepts for the lower extremities. Various tests rigs, both mechanical [4, 5] and blast driven [6], have been developed to simulate the lower extremity loading from a deforming hull due to blast loading to be able to research lower limb injury as well as mitigation methods and concepts.

Barbir [7] used the Wayne State University's linear impactor to show that a standard issue U.S. Army combat boot fitted to HIII leg can decrease peak tibia axial force by as much as 50 percent while increasing the time to peak force. Recently, Newell et al [8] compared the mitigation capabilities of three different blast mats using the MiL-Lx and the HIII legs, fitted with size 10 Meindl Desert Fox combat boot, on the Imperial College AnUBIS test rig [8] for both seated and standing positions. The axial force recorded in the MiL-Lx was always lower than that recorded in the HIII for the same severity, posture and mitigation system. Newell et al [9] also performed drop tests on the heel soles of the Meindl Desert Fox and Lowa Desert Fox combat boots and the results showed that the Meindl Desert Fox combat boot consistently experienced a lower peak force at lower impact energies and a longer time-to-peak force at higher impact energies when compared with the Lowa Desert Fox combat boot. In all these tests the reduction in the peak tibial force and delayed force rise time is a potentially positive mitigating effect in terms of the trauma experienced by the lower limb.

In this work, the mitigation capabilities of the Meindl Desert Fox and Lowa Desert Fox combat boots fitted to a MiL-lx leg are evaluated through the use of the CSIR's Modified Lower Limb Impactor (MLLI).

2. Methods and materials

The tests were conducted using the MLLI as shown in Figure 1 which consists of a spring-powered plate that impacts the surrogate leg. The MLLI allows only for vertical loaded testing using a complete ATD and is currently restricted to the seated position only. MLLI has a 32.8 kg impactor plate that can be accelerated to attain impact speeds of up to 12 m/s and a penetration of 150 mm. The peak velocity of the plate can be varied as required for the low, medium and high impact severities. The MLLI plate was instrumented with two piezo-resistive accelerometers (Endevco 7264g-2000) and two laser displacement meters (MEL M7L/400) used to capture the acceleration and the displacement, respectively. The velocity of the plate was determined from integrating the acceleration data and/ or differentiating the laser displacement.

The motion of the impactor plate and the leg were captured using a Photron SA4 and APX RS high speed video cameras. The Photron SA4 and APX cameras were both set at a frame rate of 3 000 frame per second (fps) with a resulting resolution of 1024 by 1024 pixels and used to monitor the interaction of the leg and the impactor plate..

Data acquisition was achieved through two HBM Somat eDAQ lite. The sampling speed of the eDAQ was set at 50 kHz. The eDAQs and the high speed cameras were triggered simultaneously by a laser system just before the impact of the foot or boot. The tests were executed using a 50% HIII ATD with the legs positioned in the 90°/90°/90° position of the femur, tibia and foot [10]. The MiL-Lx legs used were instrumented with two triaxial load cells (Humanetics, USA) located at the upper and lower tibia positions to capture the axial load. Two types of typical combat boots were used for these tests. These were the Meindl Desert Fox (Lucas Meindl GmbH and Co, Kirchanschoring, Germany) and the Lowa Desert Fox (Lowa Sportschuhe GmbH, Jetzendorf, Germany). The boots tested were all size 10 (UK). The thickness of the Meindl and Lowa combat desert fox boots heels were given as 40.30 mm and 37.57 mm [9] while the boots weighed 0.615 kg and 0.595 kg, respectively. Although Wang et al. [11] noted that the average velocity and acceleration of a floorplate of a medium sized armoured vehicle may exceed 12 m/s and 100 g's (1000 m/s^2) during an under AVL incident, this research focused on 6 loading conditions with a maximum of 10.2 m/s. This range was based on the NATO lower leg research [10]. Each test point was repeated three times at each loading condition for each boot type. Data processing was done using MATLAB®.

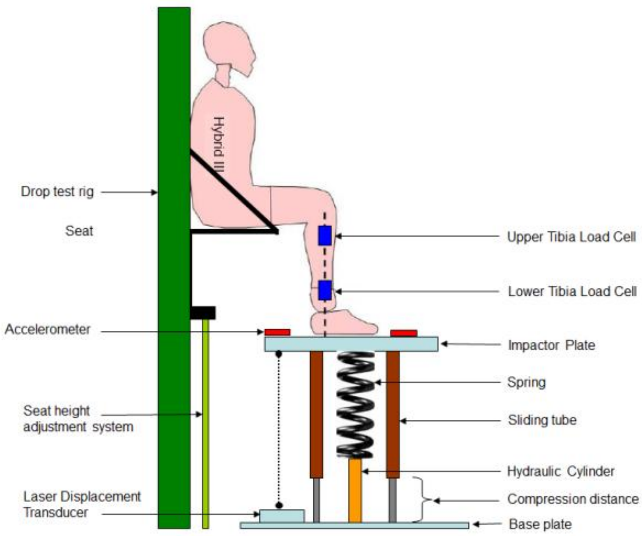

Figure 1: Experimental set-up for the MLLI [12]

3. Results

Figure 2 (a) and (b) shows the average force time response of the lower tibia (LT) and upper tibia (UT) load cells, respectively at a higher severity of 10.2 m/s loading condition with and without boots. The LT force recorded without boot shows a distinct double peak, for this study, only the first peak is used to examine and quantify the attenuation capability of the two boots. The UT peak force was taken as the maximum force recorded over the positive phase period.

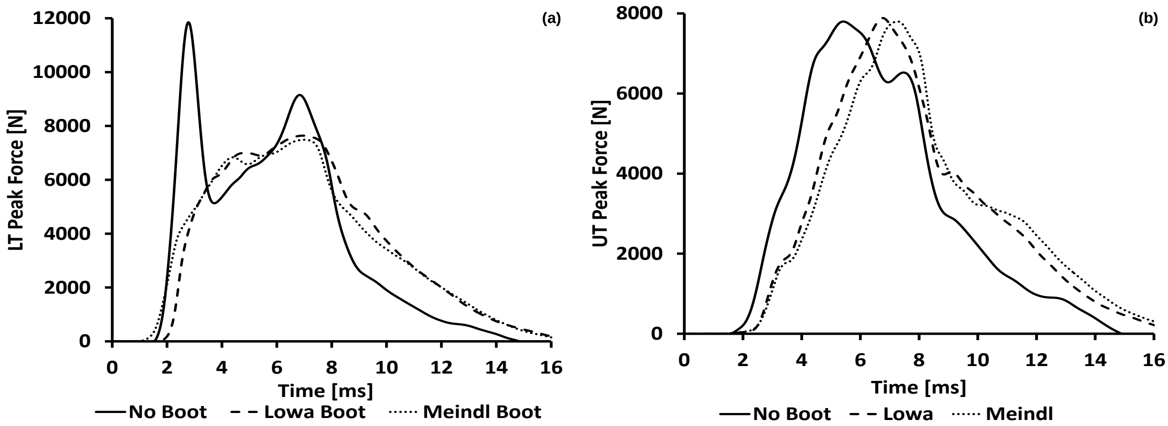

Figure 2: MiL-Lx leg force-time profile from LT (a) and (b) UT e with and without boots

The average peak force values from the LT and UT for all the tests are summarized in Figure 3 (a) and (b) respectively. The error bar shown in Figure 3 is ±1 standard deviation of the three repeated tests at the specified loading condition.

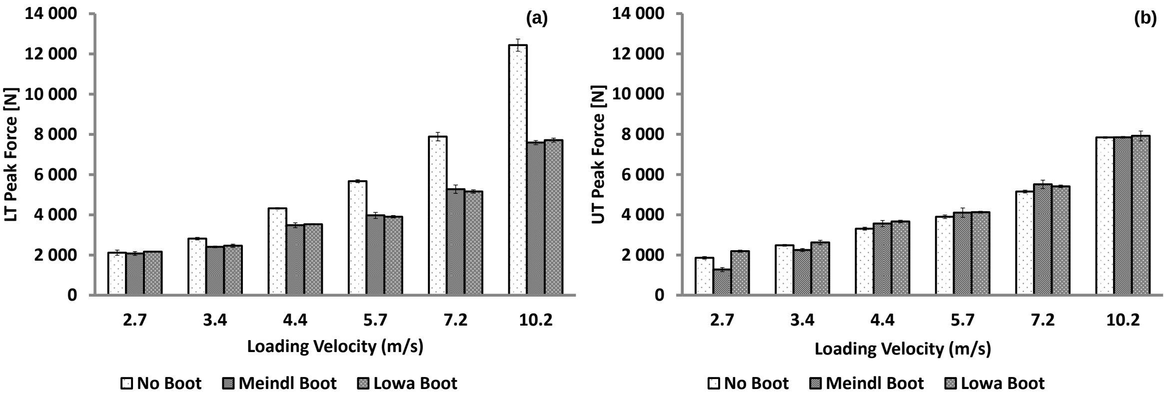

Figure 3: Average values of peak force from LT (a) UT peak force (b) with and without boot

Figure 4 shows the time- to- peak force for the LT and UT. The time was taken as the time to the first force peak.

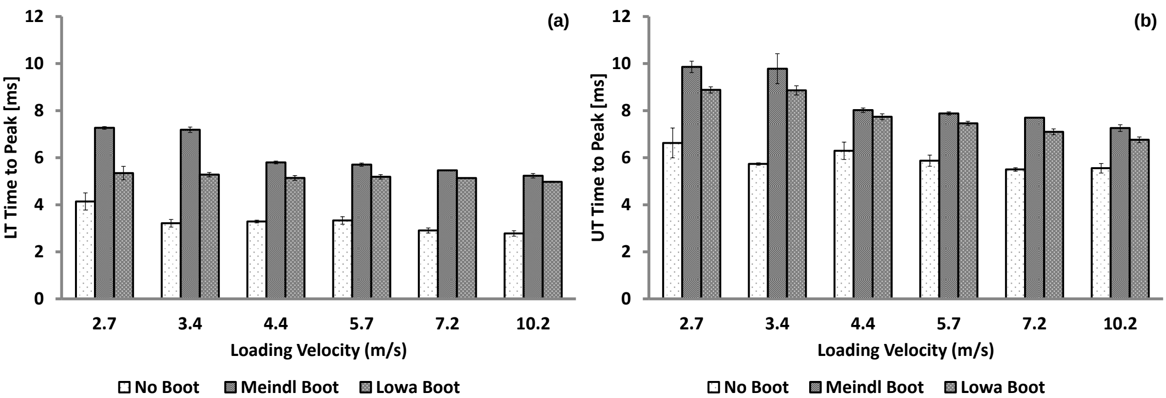

Figure 4: Average time-to-peak force values from LT (a) and UT (b) with and without boot

The average values of the impulse for the LT and UT are shown in Figure 5. The impulse was calculated by integrating the axial force from each test for the first 16 ms.

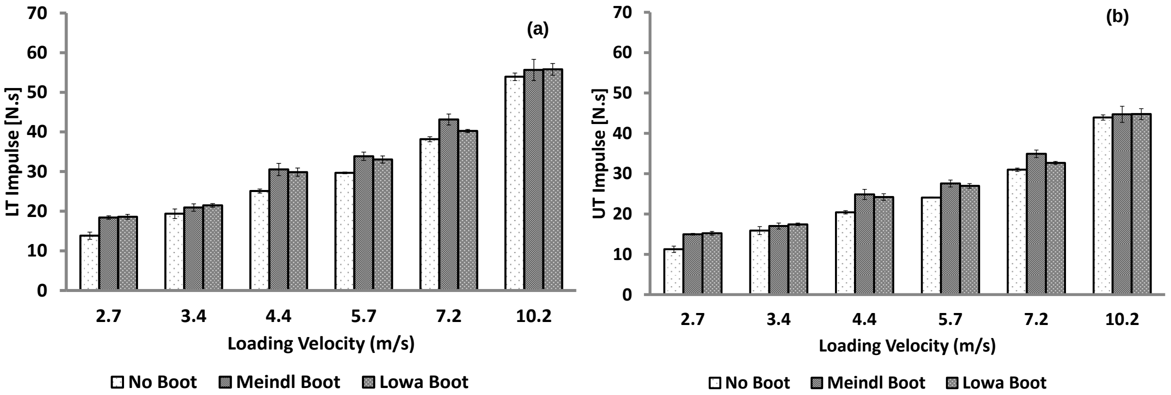

Figure 5: Average Impulse values from LT (a) and UT (b) with and without boot

4. Discussions

Figure 3 (a) compares the peak force mitigation at the lower tibia due to the presence of Meindl or Lowa desert combat boot. The MiL-Lx leg non-booted foot expectedly produces higher forces than with either the Meindl or Lowa combat boots. The Meindl and Lowa boots reduce the MiL-Lx leg LT peak force similarly. The percentage force reduction on the lower tibia increases with loading.

Figure 3 (b) compares the peak force mitigation at the upper tibia due to the presence of Meindl or Lowa desert combat boot. The MiL-Lx non-booted foot tests measured similar peak force as measured for both the Meindl and Lowa boots. This implies that as seen by the UT, the two combat boots offer no extra protection.

Only the Meindl boot had shown upper tibia peak force attenuation at the low severity impact. This attenuation is likely a function of the boot construction and possibly the elastomer's inherent dynamic compression behaviour [13]. Essentially, each elastomer exhibits a specific, behaviour to the rate of compression. Elastomers that are more tolerant of dynamic compression are likely to provide the most protection against blast impacts. This is a similar finding by [9] where the Meindl combat boot peak the force was lower than the Lowa Desert Fox combat boot. At higher energy level, both the Meindl and Lowa boots transfer a similar peak force.

Figure 4 (a) compares the time to peak force for the LT with and without boots. Both the Meindl and Lowa boots delayed the time to peak when compared to the non-booted bare foot. This effect combined with the reduction in peak force shown in Figure 3 (a) implies that the combat boots attenuated the force and delayed the transfer of load to the leg only at the lower tibia.

Figure 4 (b) compares the time to peak force for the UT with and without boots. Although the peak force measured with and without boots were similar as shown in Figure 3 (b), there was a definite delayed time to peak force with boots when compared to the non-booted foot. This implies that there is a delayed transfer of the load to the leg when there is a boot fitted. The delay in time to peak expectedly decreases as the impact severity increases.

Figure 5 (a) compares the positive impulse determined at the LT. As expected the impulse increases as the impact velocity increases for all tests. However, the boots shows higher positive impulse as compared to the non-booted test. Even though the MiL-Lx leg LT had measured a higher peak force without the boot, as shown in Figure 3 (a), a higher impulse was measured for both the boots. The impulse is proportional to the positive area under the force-time curve. The presence of the boots seem to delay the force relaxation after decoupling of the boot and the impactor plate as shown by the profile force in Figure 2 (a) after 8 ms. The presence of the boot material is attributed to this delay in relaxation and hence the increase in impulse.

Figure 5 (b) compares the positive impulse determined by the LT. The two boots shows a higher impulse than that of the non-booted test. The presence of the boots seem to delay the time-to-peak force but prolong loading to the foot by delaying force dissipation and hence contributing to the higher impulse compare with no boot. The positive impulse across all test conditions increases as the impact velocity increases.

Both the upper and lower tibia, the Meindl boot has a slightly higher total impulse when compared to the Lowa desert combat boot. This can be attributed to the higher mass for Meindl Desert combat boot relative to the Lowa Desert combat boot.

5. Conclusion

The MiL-Lx leg instrumented with the lower and upper tibia load cells has been used to evaluate the mitigation capabilities of the Meindl and Lowa Desert combat boot at six different incrementally increasing loading conditions. The results measured from the LT shows that the Meindl and Lowa Desert combat boot mitigating the peak tibia force and delayed the time to peak force. However, the results from the UT show that boots have no force reduction at high severities but only the delay in time-to-peak force. It must be noted that the Mil-Lx UT load cell is used to confirm injury risk to an in a military vehicle is exposed to AVL [10] or IED blast load. However, from the experiments, the UT does not show the potential mitigation capability of the combat boot. The positive impulse determined from both the LT and UT load cells increased when boots were fitted, thus the boots amplify the imparted impulse to the legs.

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