The Design of a Modified Lower Limb Impactor to Assess Lower Limb Injury at Typical Blast Loading Rates

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Abstract

Anti-Vehicular Landmines (AVLs), under-belly Improvised Explosive Devices (IEDs) or even side-attack IEDs are found to be some of the major threats for military vehicles and their occupants [1]. The lower extremities of the occupants are very prone to injuries, more so during underbelly detonation of the AVL or IED as a result of their spatial proximity to the rapidly deforming floor of the vehicle. Thus, there exists an urgent requirement to investigate the mechanism of extremity injury caused by AVL or IED in order to develop mitigation strategies. An important key to understanding such mechanisms of injury is the ability to deconstruct the complexities of an explosive event into a controlled, laboratory-based environment where the lower extremities can be impacted and their response evaluated.

The Modified Lower Limb Impactor (MLLI) used in the laboratory is designed to recreate the impulse that is transferred to the lower extremity from an AVL detonation. The MLLI has been built and the characterisation thereof is the main focus of this paper.

Introduction

Military operations, be it for defence against war, peace keeping or policing, all pose a risk of injury to the personnel involved in the operations. Most of the non-fatal injuries that are caused by Improvised Explosive Devices (IEDs) during the conflicts in Iraq and Afghanistan have been to the lower extremity body parts, which frequently result in either amputation or long term physical impairment [1]. The injury to the lower extremity is predominantly as a result of direct load transmission from the deforming vehicle floor which is subjected to the blast load [2]. 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) [3].

The downfall of conducting research in the field with explosives is that it is both costly and time consuming. Explosives can only be used on specifically designated, regularly inspected testing ranges, which thus adds to the inconvenience of their use. A method of performing these tests in the lab without explosives vastly increases the yield of the research. There are a number of rigs that are employed to simulate the effect of blast on the human through the use of ATDs and these all operate differently [4-9].

The CSIR has developed the Lower Limb Impactor (LLI) to simulate blast loading conditions in a laboratory environment. The LLI was designed to supply a loading force with a magnitude and duration similar to that resulting from a landmine explosive incident [8]. The LLI however was only able to reach a peak velocity of 7.2 m/s, which put it in the non-injurious and initial injurious corridors. This means that it could not reach the required over-match loading rates of 10-12 m/s which simulate injurious corridors [6].

The aim of this study is to detail the design, characterisation, and evaluation of the MLLI which is capable of recreating the floor deformation of a vehicle when it is attacked by a mine within a controlled laboratory environment.

Requirements and Design

The LLI needed modifications in order to simulate the full range of blast loading conditions. The following specifications were set to simulate an AVL threat to the occupant:

a. Acceleration of a given mass to a velocity of at least 10 m/s within less than 10 ms time to peak force.

b. Rapid deceleration of the mass after reaching the target velocity in order to simulate the floor's deceleration and return to rest. This assumes no dynamic deflection of the impactor plate.

c. Ability to mount a surrogate leg in a variety of orientations that simulate an occupant's typical postures within a vehicle; for example seated, standing, or driving.

Design of the MLLI

The final design of the MLLI is shown in Figure 1. The MLLI consists of a compression spring, hydraulic cylinder, pump, impacting plate, four stabilising cylinders and sliding tubes and a swivelling hook release mechanism. A bigger spring compared to that used in the LLI was installed to accelerate the impactor plate to a velocity of at least 10 m/s. The properties of the spring used were as follows: spring constant of 187 N/mm, free length of 500 mm, bar diameter of 32 mm and mean diameter of 213 mm.

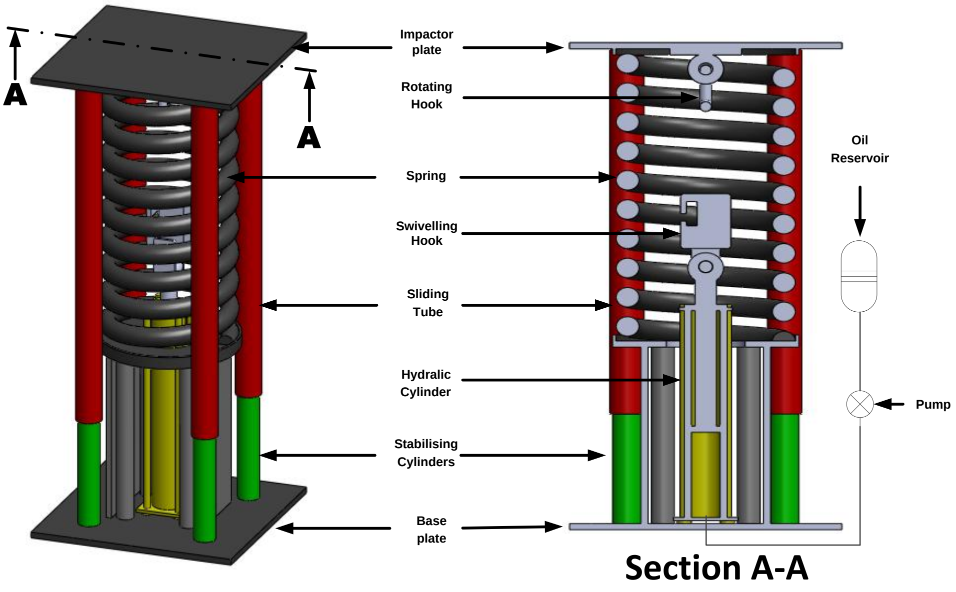

Figure 1: Schematic of the MLLI and its components

The compression of the spring is carried out by attaching the hydraulic cylinder to the impact plate via a swivelling hook release mechanism and pumping the cylinder down. The degree of the compression of the spring varies the maximum velocity of the impactor plate, which achieves the desired velocity when the spring has decompressed to its full height.

The swivelling hook release mechanism shown in Figure 2 was designed to achieve an instantaneous release of the impactor plate. The components of the swivelling hook release mechanism were manufactured from a Weldox 700 plate with a yield stress of 700 MPa to cope with the high force induced during compression. The rotating hook is attached to the impactor plate and the swivelling hook is attached to the hydraulic cylinder. The rotating hook and the swivelling hook are locked by the locking plate before the spring is compressed. To create an instantaneous release of the impactor plate from the compressed spring, the locking plate is rotated downwards by pulling it with a steel wire.

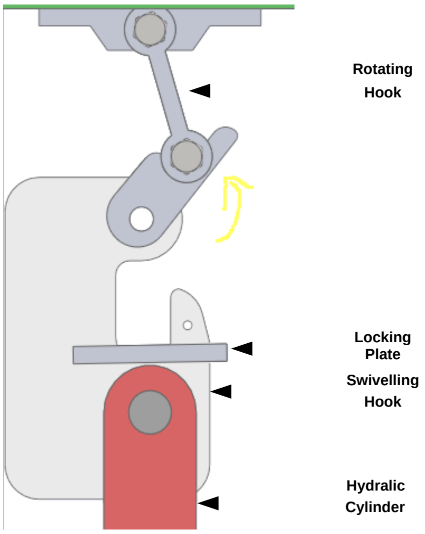

Figure 2: View of the Swivelling Hook Release Mechanism in a Released Position

A hydraulic system with a longer cylinder compared to the LLI was installed. The hydraulic cylinder is pumped up or down through the use of a dual action hand pump. A taller base was manufactured to heighten the entire system to allow for the complete extension and retraction of the hydraulic piston.

The impactor plate and the sliding tube are connected to become a unit to ensure that the plate does not tilt when it propagate upwards.

The combined mass of the impactor plate and sliding tube components which are accelerated on top of the spring summed up to be 32.8 kg. The impactor plate – sliding tube system can be propelled to velocities of up to 10 m/.

Instrumentation of the MLLI

Two piezo-resistive accelerometers (Endevco 7264g-2000) were used to measure the acceleration of the plate during the tests. The accelerometers were mounted on opposite ends on the top of the impactor plate. The accelerations values were filtered using a CFC 600 software filter as recommended by NATO standard [10]. The accelerations values from the accelerometers were integrated to determine impactor velocity.

Two Laser Displacement Meters (LDM), MEL M7L/400 type, were used to measure the displacement of the impactor plate. LDMs were mounted on each side of the MLLI to measure the level of the plate during testing and to check how well the impactor plate was balanced when it was accelerated. One of the LDM was used as a trigger signal generator using a set distance.

The LDMs have a measuring range of 0.5 to 400 mm of the plate movement and it operates at 10 kHz. During testing these sensors were connected to an electronic module for power and data transfer. The module was powered by a 24 V DC power supply and has an indicator Light Emitting Diode (LED) to indicate if the distance measured is within its operating range.

The displacement values of the impactor plate were filtered using a low pass Butterworth filter at 1000 Hz as recommended by the NATO standard [10]. The derivative of the displacement values was utilized to determine the impactor velocity of the impactor plate.

The motions of the impactor plate and the surrogate leg were captured using Photron SA4 and APX high speed video cameras. The Photron SA4 and APX cameras were both set at a frame rate of 3 000 frames per second (fps) with a resulting resolution of 1024 by 1024 pixels. Light source in the form of LED, halogen and AC lights were used to provide the required luminance for the video footage. For example, when using a 4 x 6 LED array positioned at 2 m relative to the MLLI, the camera shutter speed set in the range of 250 to 500 microseconds and the camera speed set about 1 000 fps, 32 000 lux is obtained. The lights used achieved the required luminance during all tests which was measured with the Extech Easyview 33 light meter.

The high speed video cameras were synchronised for capturing the impact of the surrogate leg using the trigger signal from the triggering laser displacement system.

Two electronic data acquisition units (eDAQ lites) controlled with a Test Control Environment (TCE) software were used to capture the accelerations and displacement data during the tests. The sampling speed of the eDAQ was set at 50 kHz. Figure 3 shows a data link between the accelerometers, LDMs and the capturing eDAQ lites. Also shown in Figure 3 is the triggering signal to synchronise the release of the impactor plate and the initiation of data capturing.

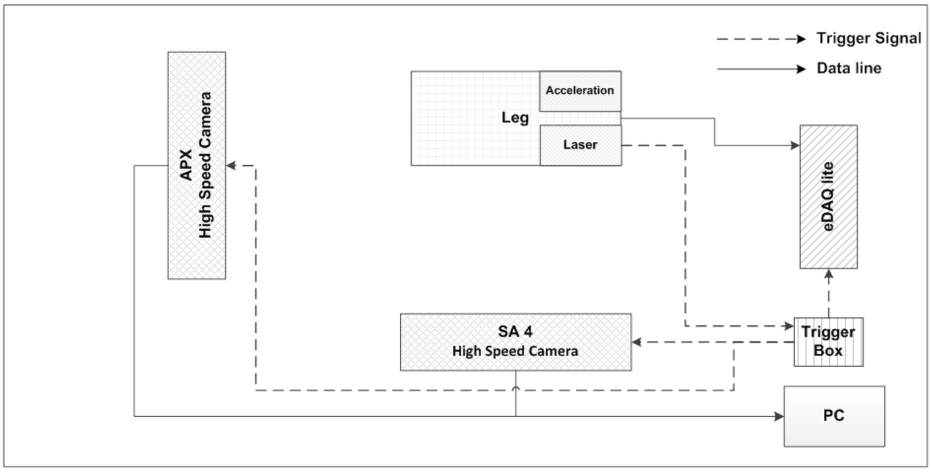

Figure 3: The Triggering and Data Line used during the Test with the MLLI

Evaluation of the MLLI

Figure 4 shows the MLLI bolted on the floor and the ATD positioned on the drop test rig. The setup allowed for single or double impact which refers to the use of one or two legs, respectively. The foot of the surrogate leg was positioned on the MLLI with ankle and knee joints at 90° flexion to simulate a seated occupant not wearing a boot. The surrogate leg is held in position using a small wire while the impactor plate is withdrawn when the spring is hydraulically compressed. The impartation of the leg in this manner simulates the dynamics of a floor of an armoured vehicle.

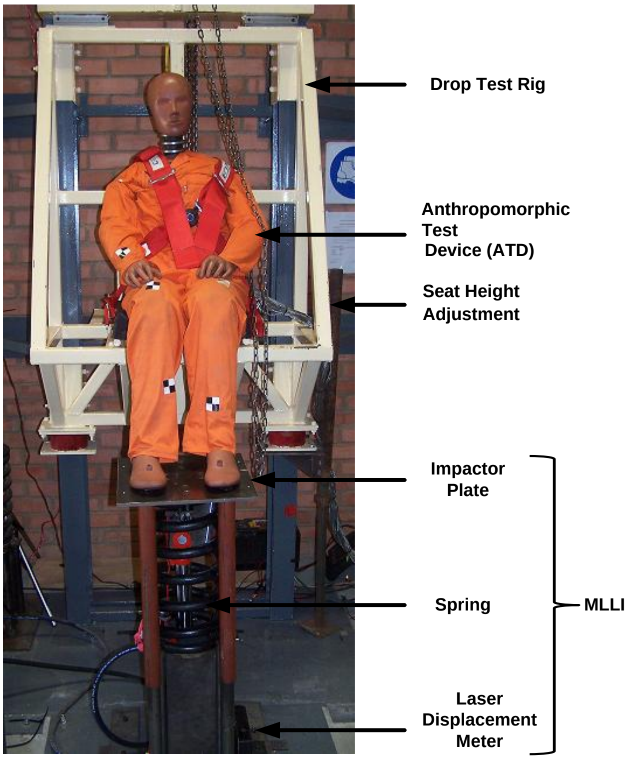

Figure 4: MLLI Test Setup with an Instrumented ATD

In order to evaluate the MLLI, it was used to impact the surrogate leg at loading conditions which are well characterised and where the response of the surrogate leg is known. The MiL-Lx leg was previously characterised at loading condition of 7.2 m/s and its response was recorded [5]. This loading condition was used to evaluate the MLLI with the setup shown in Figure 4.

Results

The MLLI was able to achieve a velocity of at least 10 m/s. The velocity and flight traces calculated by the accelerometer data were compared to the data obtained by laser displacement. Good agreement between the two methods of data acquisition was observed; maximum differences in plate displacement, maximum velocity and time at maximum velocity were less than 5%. The characterisation was at done at 7.2 m/s due to there being enough data available for the comparison with the MiL-Lx leg at that velocity.

Figure 5 shows the force-time trajectories measured the MiL-Lx leg upper tibia load cell using the MLLI. The time to peak for the upper tibia force was within 5 ms for the impactor at a maximum velocity of 7.2 m/s.

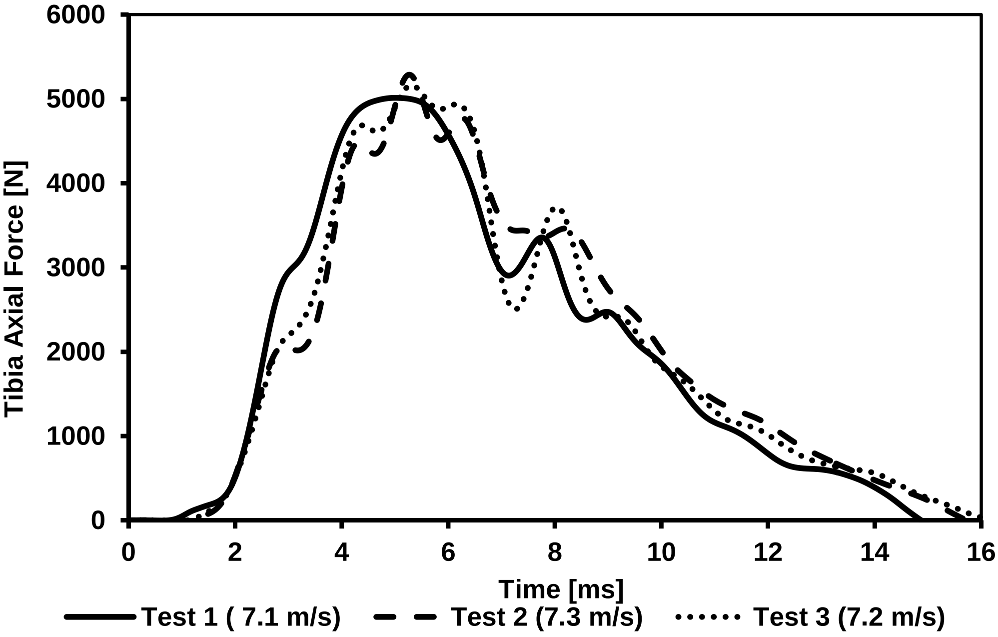

Figure 5: MiL-Lx leg Response to 7.2 m/s Loading

The MiL-Lx leg upper tibia peak force averaged 5154 N and ranged from 5013 N to 5161 N. The MiL-Lx leg's biomechanical response demonstrated high repeatability with a standard deviation of 137 N for the tibia peak load.

Discussion

Figure 6 shows the comparison of cadaveric results with the MLLI MiL-Lx leg results. It can be concluded from the results that the MLLI at 7.2 m/s gave similar results compared to the WSU impactor PMHS's tests.

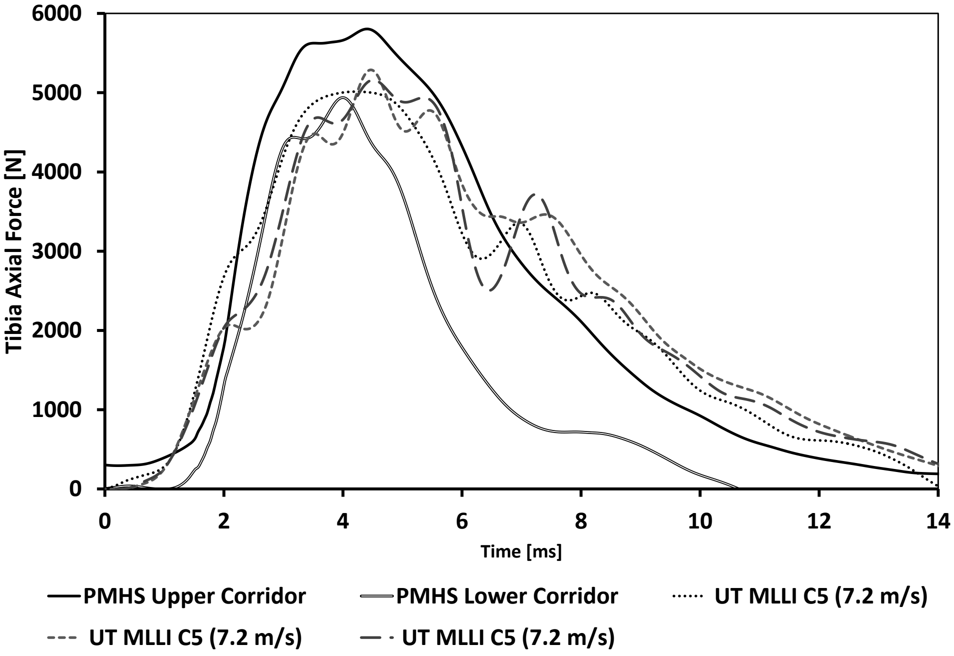

Figure 6: Comparison of MLLI Results with Cadaveric Corridors Developed by Mckay [6]

The MiL-Lx data presented here can be directly compared with McKay MiL-Lx leg studies at 7.2 m/s [6]. The response of the upper load cell was a typical bell shaped curve with maximum axial force of 5154 ± 187 N at 4.8 ± 0.2 ms. Mckay reported the time to the peak force of 5361 ± 181 N within 4.2 ms for impactor speeds of 7.2 m/s, which is similar to the force and time in the MiL-Lx leg experiments presented here.

The MiL-Lx leg upper tibia peak axial force measured at 7.2 m/s was less than the force measured at WSU C1 but within the error bar, the difference was less than 4%. The difference is due to the difference in the impactor plate mass of the two test rigs resulting in different impactor kinetic energy. The impactor kinetic energy utilized in this study ranged from 120 to 2238 J and was less than the 859 to 2752 J range used by Mckay [6]. Figure 7 shows the comparison of the PMHS, WSU and MLLI tests with the MiL-Lx leg.

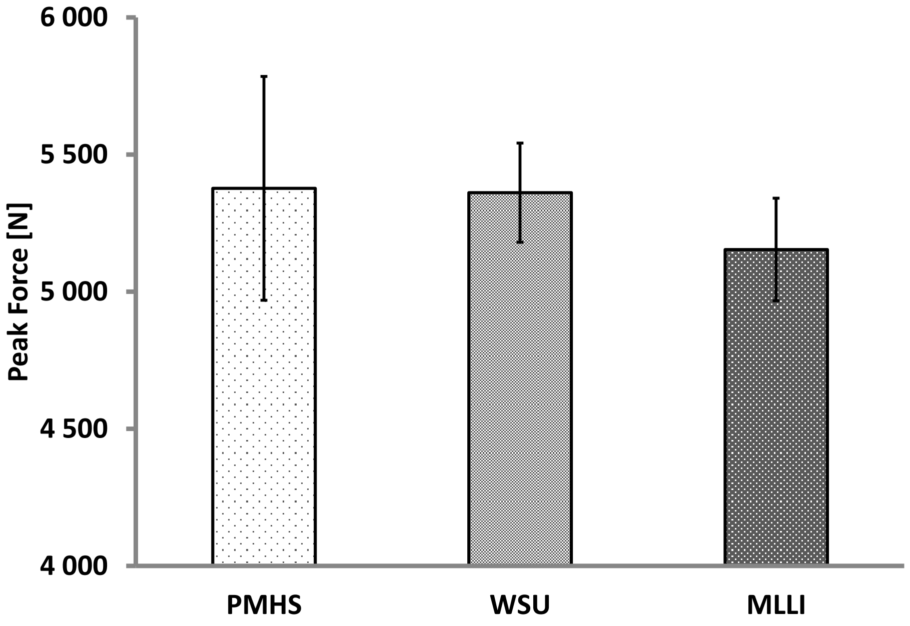

Figure 7: Comparison of MLLI and WSU MiL-Lx leg Peak Force Compared with PMHS response

The motion characteristics of the floor of a vehicle subjected to a mine blast can be affected by a number of factors; for example size of charge, depth of burial, properties of soil and design of vehicle, to name but a few [11]. In the MLLI design described here, the objective was to allow for a range of impulse characteristics to be simulated, representing various levels of threat within the realm of a laboratory. In addition, the pulse transferred to and the severity of the injury sustained by each extremity of each occupant for a specific set of AVLs blast characteristics may depend on the occupant's posture and position within the vehicle, amount and type of personal protection equipment, and occupant biometrics. Considering the multitude of parameters involved in a complex event such as AVL blast, the MLLI tool will enable strides to be made towards understanding the mechanism of injury.

Conclusions

The experimental apparatus presented here allows for biomechanical lower limbs surrogates to be tested at various postures, and offers an independent test-bed for assessing the bio-fidelity of the response of leg-surrogates. It provides a platform for understanding mechanisms of load transfer and of injury and as such for evaluation of current, and development of new injury mitigation technologies such as boots and floor energy absorbing mats.

When a vehicle is struck by an AVL, the feet of the occupants are likely to be off the floor at the time of detonation resting on the foot rest. As such, the occupants' limbs are impacted by the accelerating floor. Unlike other injury simulators that accelerate the lower limb, with the MLLI, a surrogate leg is impacted by the accelerating plate; hence it can be argued that this apparatus is most likely to replicate the loading mechanism occurring in an AVL blast. The spring compression relates directly to the energy that is being transferred by the plate to a surrogate leg and is therefore a reproducible quantity; consequently, in subsequent works the metric defining the ‘threat’ in MLLI shall be the compressed height of the spring.

Acknowledgments

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