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Impact loading response of the MiL-Lx leg fitted with combat boots

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ABSTRACT

Anti-Vehicular Landmine or under-belly Improvised Explosive Device (IED) or even a side-attack IED are found to be one of the major threats for military vehicles and their occupants. The lower extremities of the occupants are very prone to the injuries more especially during underbelly detonation due to the spatial proximity to the rapid deforming floors. Lower limb surrogate legs, such as the Hybrid III (HIII) or Military Lower Extremity (MiL-Lx) are used to quantify the loading on the lower extremity when subjected to the impulsive loading caused by such an explosive event. Military boots could be used by the occupants to mitigate the blast loading impact on the lower extremities. This work presents 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 boots using the MiL-Lx leg. The blast loading conditions were simulated using the modified lower limb impactor at several loading velocities spanning 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 show 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 boot shows a better peak force attenuation than the Lowa boot at the upper tibia. Both boots show 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 boot. Both boots show 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.

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 impulsive loading on the vehicle occupants, instrumented lower limb surrogate legs are used in conjunction with a specified Anthropomorphic Test Device (ATD) [2].

For lower limb surrogate legs to be an appropriate tool measuring axial impact loading and assess the associated injury potential, it must have an impact response similar to that of the natural human leg. Previous studies have demonstrated the low biofidelity of the current standard ATD leg, the Hybrid III (HIII). The HIII leg, sometimes called DENTON-Leg is part of the HIII ATD original equipment [3]. The ankle assembly consists of a ball and socket joint with an adjustable frictional resistance level. The level of frictional resistance is controlled by a setscrew at the ankle ball that can be tightened to increase the ankle's resistance to motion.

The Hybrid III leg constitutes a steel tube, connected to the knee via a fork at the top end and with a simple ankle at the bottom end to which the foot is attached. The HIII leg has no cushioning or equivalent elements except the foot elastometer and heel pad.

Due to the poor performance of the HIII, the The Test Device for Human Occupant Restraint (THOR-Lx) leg was developed by the National Highway Traffic Safety Administration [4]. The THOR-Lx is an improvement as compared with HIII leg, because it incorporates significantly improved biofidelity and expanded injury assessment capabilities. Thanks to its enhanced design and measurement capabilities, THOR-Lx offers numerous functional benefits as compared to the HIII leg, including detailed assessment of foot motions and ankle/foot/tibia injury potential.

Bir et al [7] conducted impact tests on THOR-Lx leg and reported that the leg provides more accurate correlation with cadaveric

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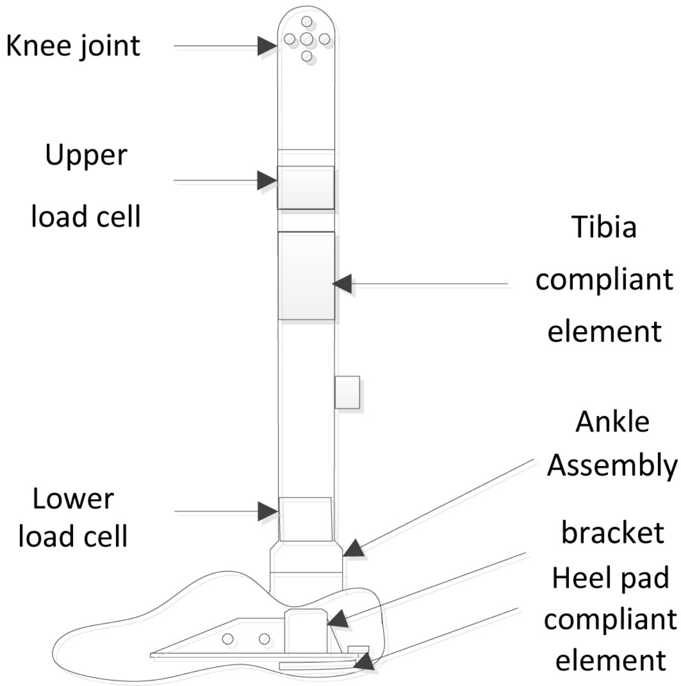

Figure 1. Military Extremity Leg (MiL–Lx) [6].

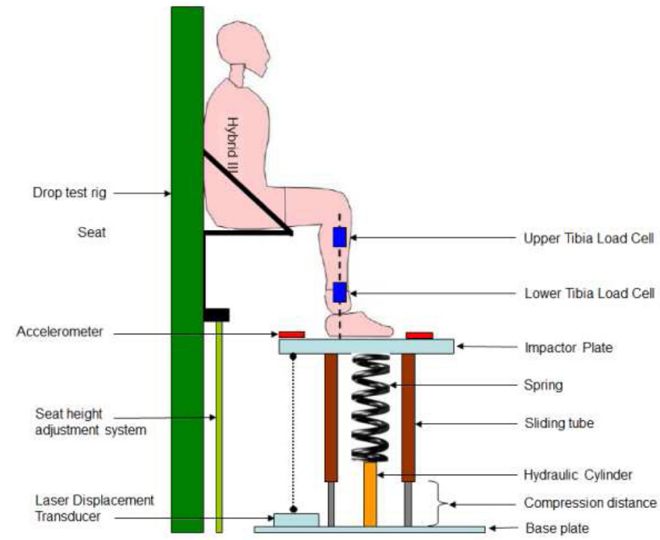

Figure 2. Experimental set-up for the MLLI (Reproduced from [9]).

test data than the HIII at low impulsive loads. This study also revealed that there is a loss of biofidelity in both HIII and THOR-Lx at higher loading conditions. The Thor-Lx was limited in its ability to properly represent the response of the human lower leg at higher loading conditions [7]. This was attributed to the compressive limits of the compliant element. These findings suggest that neither of these surrogates can be used for evaluation of AVL blast injuries.

This led to the development of the military lower extremity (MiL-Lx) leg (Figure 1). The MiL-Lx leg was designed for impact loading of the foot reflecting the vehicle floor response for condition 4 loads [5] and velocities presenting AVL structural response. This advanced design incorporates aspects of both the standard HIII and the THOR-Lx leg.

The MiL-Lx is a straight leg design with absorbing elements, optimized for vertical compression forces and velocities. The THOR-LX tibia compliant element was adopted into the MiL-Lx design. The compliant element was doubled in length from five to ten centimeters in the MiL-Lx to enable additional room for compression. The compliant element enables the tibia shaft to provide an attenuated force transmission from the heel to the knee complex. The compliant element rests between the upper and lower tibia tubes, which hold the upper and lower tibia load cells respectively. It is more biofidelic for AV mine loading conditions, simple and robust [5].

During development of this surrogate, its response was evaluated under impact loading and compared to cadaveric tibia axial force data for selection of the new compliant element [8]. However, the axial force was only compared to cadaveric results at a single impact velocity (7.1 m/s) and, as such, the biofidelity of this surrogate has yet to be examined over a range of velocities. The MIL-Lx may be proposed to be the new standard tool for military testing and, as such, its response to impulsive loading needs to be properly characterised.

Instrumented military vehicles are subjected to the specified series of live explosive blast tests. The surrogate leg captures test information such as the transferred lower leg load; displacement and acceleration of the lower limb are captured. 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 and blast driven, 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.

As examples; Barbir [4] used 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 [5] 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 for both seated and standing positions. Newell et al [6] have also performed drop tests on 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 which consist of a spring-powered plate that impacts the surrogate leg (Figure 2). The MLLI allows only for vertical loaded testing using a complete ATD and is currently restricted to the seated position only. Previous research suggested that in under vehicle explosions the floor can reach velocities of 12 m/s within 10 ms [7]. MLLI has a 32.8 kg impactor plate that can be accelerated to attain impact speeds of up to 12m/s within 10 ms and a floor penetration of 120 mm. The peak velocity of the plate can be varied as required for the low, medium and high impact severities. The MLLI itself is instrumented with two piezo-resistive accelerometers and two laser displacement meters used to capture the acceleration and the displacement of the impactor plate, respectively. The velocity of the plate was calculated