Use of cadavers and anthropometric test devices (ATDs) for assessing lower limb injury outcome from under-vehicle explosions.

Nicolas Newell, Spyros D Masouros, Arul Ramasamy, Timothy J Bonner, Adam M Hill,
Jon C Clasper, Anthony MJ Bull

Abstract Lower extremities are particularly susceptible to injury in an under-vehicle explosion. Operational fitness of military vehicles is assessed through anthropometric test devices (ATDs) in full-scale blast tests. The aim of this study was to compare the response between the Hybrid-III ATD, the MiL-Lx ATD and cadavers in our traumatic injury simulator, which is able to replicate the response of the vehicle floor in an under-vehicle explosion. All specimens were fitted with a combat boot and tested on our traumatic injury simulator in a seated position. The load recorded in the ATDs was above the tolerance levels recommended by NATO in all tests; no injuries were observed in any of the 3 cadaveric specimens. The Hybrid-III produced higher peak forces than the MiL-Lx. The time to peak strain in the calcaneus of the cadavers was similar to the time to peak force in the ATDs. Maximum compression of the sole of the combat boot was similar for cadavers and MiL-Lx, but significantly greater for the Hybrid-III. These results suggest that the MiL-Lx has a more biofidelic response to under-vehicle explosive events compared to the Hybrid-III. Therefore, it is recommended that mitigation strategies are assessed using the MiL-Lx surrogate and not the Hybrid-III.

Keywords Blast injury, Cadaver, Hybrid-III, IED, MIL-Lx

Nicolas Newell is a PhD student in the Department of Bioengineering, Imperial College London, UK.
Spyros D Masouros is the ABF – The Soldiers' Charity Research Fellow in the Department of Bioengineering, Imperial College London, UK (Tel: +44 20 75942646, Fax: +44 20 75949817, email: s.masouros04@imperial.ac.uk).
Timothy J Bonner is an MD and Arul Ramasamy a PhD student in the Department of Bioengineering, Imperial College London, UK & Research Fellows in the Academic Department of Military Surgery and Trauma, Royal Centre for Defence Medicine, Birmingham, UK.
Adam M Hill is an Honorary Lecturer in the Department of Bioengineering, Imperial College London.
Andrew TH West is Consultant Radiologist in the Centre of Defence Imaging, Royal Centre for Defence Medicine, Birmingham, UK.
Jon C Clasper is a Visiting Professor in the Department of Bioengineering, Imperial College London & Defense Professor in Trauma and Orthopaedics in the Academic Department of Military Surgery and Trauma, Royal Centre for Defence Medicine, Birmingham, UK.
Anthony MJ Bull is Professor of Musculoskeletal Mechanics in the Department of Bioengineering, and Director of the Royal British Legion Centre for Blast Injury Studies at Imperial College London, UK.

I. INTRODUCTION

The improvised explosive device (IED) has been the weapon of choice by insurgents in recent conflicts [1]. The majority of non-fatal injuries to coalition troops in Iraq and Afghanistan have been to the lower extremities [2]. Most commonly, lower extremity injuries are sustained by casualties in enclosed environments, for example in vehicles [2]. An explosion under a vehicle causes rapid local deformation of the floorpan, which in turn transfers high-rate axial loading to the occupant’s lower extremities [2].

Military vehicles are assessed to determine the level of protection they offer against the threat of anti-vehicle landmines through full-scale live blast tests. In these tests, human surrogates are used to assess body loading. The North Atlantic Treaty Organisation (NATO), who provides protocol recommendations for the full-scale live-blast tests, selected the Hybrid-III antropometric test device (ATD) as the most appropriate existing surrogate [3]. More recently, a new ATD lower extremity specifically designed for anti-vehicle blast research, called the Military Extremity (MiL-Lx), has been developed and is included in the most recent protocol recommended by NATO [4]. Injury risk models determined through tests of cadaveric lower limbs have been used to assign tolerance values for the ATDs [5-6]. For both ATDs these values are of the compressive force recorded at the surrogate tibia. For the Hybrid-III the tolerance value is 5.4 kN recorded at the lower tibia load cell and for the MIL-Lx is 2.6 kN recorded at the upper tibia load cell; the difference in value is due to the difference in ATD design and location of the sensor.

Both the Hybrid-III and MiL-Lx ATDs are multi-use surrogates, which are designed to represent the mass, mass distribution and geometry of the human body; however, due to their lack of frangibility and crude geometry they are simplistic representations of the complex functional anatomy of the human lower limb. Efforts to compare the response of the ATDs to cadavers are valuable to understand the limitations of these surrogates. The response of both the Hybrid-III and MiL-Lx has been compared to cadavers previously using the same experimental platform; the MiL-Lx had a more biofidelic response [7-8]. However, the methodolgy used for these cadaveric tests involved the removal of 90 mm of the tibia to insert a load cell [8] and it has been argued that the removal of this section of tibia is likely to affect the behaviour of the cadaver when impacted [9].

The aim of this study is to compare the response of the Hybrid-III and the MiL-Lx against intact cadavers using a customised traumatic injury simulator.

II. METHODS

Previous research has suggested that in under vehicle explosions the floor can reach velocities of 12 m/s within 10 ms [10]. AnUBIS (Anti-vehicle Underbelly Blast Injury Simulator) is capable of accelerating a 42 kg mass to 9 m/s within 10 ms (Fig. 1). The moving plate sits within a pressure vessel which is held in place by a tie rod, secured with a cross pin at the top and a nut, tightened beneath the pressure vessel, at the bottom. Compressed air is released into the pressure vessel until the force acting on the pin is high enough for it to shear, allowing the plate to accelerate upwards. The peak velocity that the plate reaches can be adjusted by selecting different shear pin materials and dimensions. The deceleration of the plate is achieved by allowing its lugs to be wedged between four pairs of breaking arms. The breaking arms are fixed with a pin joint at the bottom and highstiffness springs at the top. As the breaking arms are pushed open, the springs provide a reaction force that brings the plate to rest.

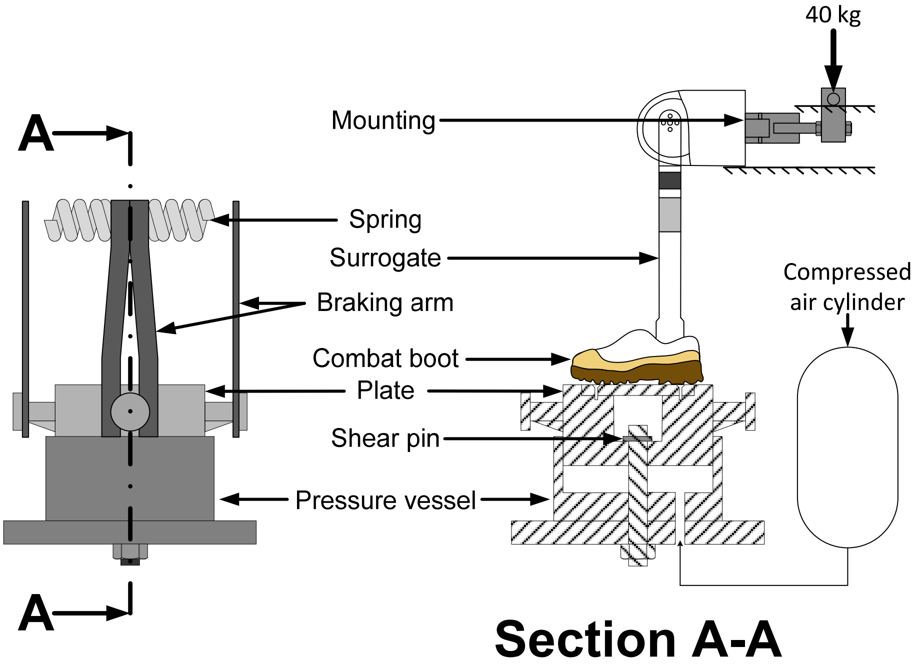

Fig. 1. Design of the anti-vehicle underbelly blast injury simulator (AnUBIS). The surrogate and compressed air cylinder has been added to Section A-A.

The ATD or cadaveric specimen was fitted with the sole of an appropriately sized Meindl Desert Fox combat boot (Lucas Meindl GmbH and Co, Kirchanschoring, Germany) and mounted onto AnUBIS in a seated position with the foot resting on the plate. The knee was positioned directly above the ankle and the thigh was positioned horizontally. Specimens were connected to a surrogate hip joint that allowed six degrees of freedom motion. The surrogate hip joint was loaded with 40 kg to represent a typical half body weight.

The cadavers were fresh frozen at -20°C and were thawed overnight prior to testing. All cadaveric specimens underwent computed tomography (CT) scanning (Siemens Somatom Definition AS 64; Erlangen, Germany) before and after testing to assess for injury. The proximal femur was removed and the femoral canal was reamed allowing a threaded M12 steel studding to be inserted 150 mm into the canal and secured with bone cement (PMMA). A pot was slid down the intramedullary rod and a nut was tightened behind it, such that the pot was pressing against the femur. Screws in the side of the pot were tightened to fix the femur in place and the pot was then filled with bone cement.

Both ATDs are instrumented with triaxial load cells in the tibia; the Hybrid-III had two load cells (upper and lower tibia) while the MiL-Lx had just one (upper tibia). The tolerance level recommended by NATO is associated with the load in the lower tibia of the Hybrid-III and upper tibia in the MiL-Lx [4]. Therefore ATD load data presented in this study is taken from those load cells. All load cells were sampled at 25 kHz. The cadaveric specimens were instrumented with strain gauges (CEA-06-125UW-350, Vishay, Basingstoke, UK) that were fixed to the medial and lateral aspects of the calcaneus. In order to mount the strain gauges the soft tissue was removed from the medial and lateral aspects, the bone was dried with ethanol and the strain gauges were adhered using cyanoacrylate. The strain gauges were sampled at 25 kHz by a National Instruments PXIe system (Newbury, Berkshire, UK), utilising a custom written LabView code (NI, Newbury, Berkshire, UK).

Fig. 2 shows diagrams of the Hybrid-III, MiL-Lx and cadaver. The design of the MiL-Lx differs from the Hybrid-III in 3 distinct ways, 1) it has a 70 mm long compliant element in the leg shaft 2) the leg shaft is straight and not offset from the vertical and 3) it has a support bracket on the plantar aspect of the foot.

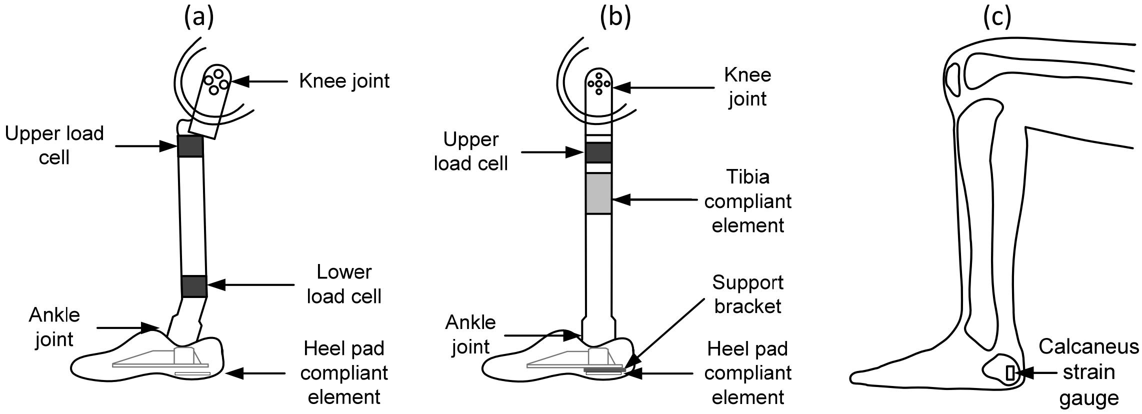

Fig. 2. Diagrams showing the geometry and instrumentation of (a) the Hybrid-III (b) the MiL-Lx and (c) a cadaveric specimen. Diagrams are not to scale.

AnUBIS was instrumented with a pressure transducer (Pi602, Applied Measurements, Berkshire, UK) attached to the pressure hose which feeds into the vessel beneath the accelerating mass. An accelerometer (model 352C04, PCB Piezotronics Inc., NY, USA) was mounted to the surface of the impacting plate. Both pressure transducer and accelerometer were sampled at 25 kHz using the National instruments PXIe system and custom written LabView code mentioned previously. A Phantom V12.1 (4000 fps) high speed video (Vision Research, Bedford, UK) was used to film the displacement of the plate and the compression of the medial aspect of the heel of the combat boot during the tests. Data acquisition for all instrumentation was triggered from a single source to ensure synchronisation. Compression of the combat boot and displacement of the plate were calculated utilising the high speed video. Specifically, compression of the boot was calculated as the difference between tracked pixels at top and bottom of the outer part of the combat boot. The velocity profile of the plate was calculated by integrating the accelerometer signal and confirmed by differentiating the displacement data obtained from the high speed video. An anti-aliasing filter was used on accelerometer, pressure transducer and strain gauges as part of the PXIe data acquisition system. A CFC 600 filter was used on both the Hybrid-III and MiL-Lx load data as per NATO standard recommendation [11].

A 12.7 mm brass shear pin was used for all tests; this was expected to result in a maximum plate velocity of approximately 9 m/s. Both ATD designs were tested 3 times. 3 intact specimens were used for the cadaveric experiments. Tests were performed at room temperature (22 ± 1°C) and a new appropriately sized combat boot was used for every experiment. The viscoelastic materials of the dummy were given at least 30 minutes to relax between tests. The behaviour of the ATDs was compared to that of the cadavers using 3 criteria; 1) the predicted injury level, 2) the time to reach peak force/strain, and 3) the combat boot compression fitted to each surrogate.

III. RESULTS

The pressure at release for all surrogate tests was 9.2 ± 0.3 bar. There was no significant difference between the pressure profiles for the cadaveric and ATD tests. There was no significant difference between the three surrogates in terms of maximum plate flight (141.6 ± 11.6 mm), maximum velocity (9.2 ± 0.6 m/s) or time to maximum velocity (9.3 ± 1.1 ms).

Anthropometric and physical details for the 3 cadaveric specimens are presented in Table 1. CT scans revealed that there were no skeletal injuries post-impact in 2 out of the 3 cadavers; the third had a minimally displaced extra-articular fracture of the medial aspect of the mid-calcaneum, which is considered a minor injury from which the causality is expected to recover fully. An instrumentation failure meant that acceleration, strain and pressure data were not recorded for the second cadaveric specimen.

TABLE I

ANTHROPOMETRIC AND PHYSICAL DATA OF CADAVERIC SPECIMENS

Specimen	Age (years)	Gender	Height (m)	Weight (kg)	Left/Right	BMI
1	40	Male	1.78	66	L	21
2	27	Male	1.75	78	R	25
3	48	Male	1.90	88	L	24

Average axial force on the Hybrid-III lower tibia is compared to the MiL-Lx upper tibia in Fig. 3. The Hybrid-III consistently experienced a higher maximum force than the MiL-Lx (10.17 ± 0.67 kN compared to 5.60 ± 0.10 kN). The maximum loads from all 3 Hybrid-III tests and all 3 MiL-Lx tests were above the tolerance level recommended by NATO for each ATD [4].

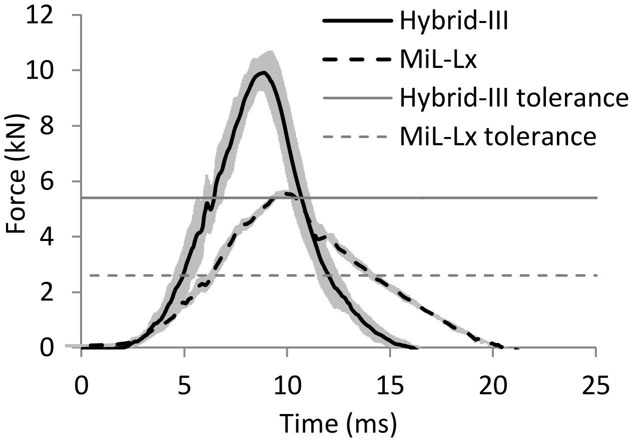

Fig. 3. Comparison of Hybrid-III and MiL-Lx average force-time curves. The shaded region represents ± 1 standard deviation. The tolerance level recommended by NATO is 5.4 kN for the Hybrid-III and 2.6 kN for the MiL-Lx [4].

The average time to peak compressive strain for the cadaveric specimens and load for the ATDs is compared in Fig. 4a. The cadaveric specimens reached peak compressive strain in a time similar to that taken for the Hybrid-III and MiL-Lx to reach peak compressive load. The maximum boot compression for all three surrogates is compared in Fig. 4b. The maximum boot compression in the cadaveric and MiL-Lx tests was considerably lower than the Hybrid-III tests.

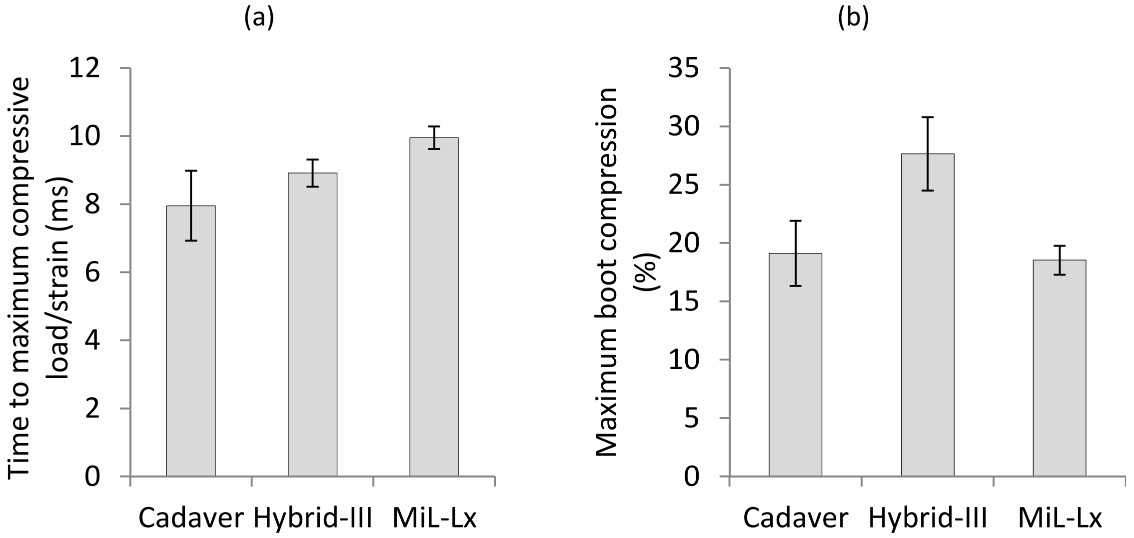

Fig. 4. Comparison of all three surrogates in terms of (a) time to maximum compressive strain for the cadaveric specimens and maximum compressive load for the ATDs and (b) maximum combat boot compression for both ATD designs and cadaveric specimens.

IV. DISCUSSION

The loads experienced by the ATDs were consistently above the tolerance levels recommended by NATO (on average, 1.88 times greater for the Hybrid-III tests and 2.15 times greater for the MiL-Lx tests) [4]; however, minor or no injuries were seen in the 3 cadaveric specimens. The population affected by under-vehicle explosions is likely to be young military personnel. While the average age of the cadaveric samples used in this study is young (38.3 years) compared to the studies that developed the injury tolerance levels (67 years [5] and 56 years [6]), it is still older than the expected affected population. The old age of the samples used to produce the injury criteria combined with the results from the experiments presented in this paper suggest that the tolerances for both ATDs are conservative.

Another reason for the seemingly conservative injury tolerances values could be the experimental methods that have been used to derive them. The Hybrid-III tolerance values were developed from a series of 52 cadaveric lower leg impacts [6]. In these experiments the knee was disarticulated, leaving just the lower extremity distal to the knee joint intact; the proximal end was rigidly fixed to a 'mini sled' and then the leg was impacted at the foot. In an axial impact knee flexion is likely to provide a mechanism of energy dissipation. Therefore, omitting the knee joint and hence changing the physiological boundary condition proximally might have contributed to the seemingly conservative tolerance values developed for the Hybrid-III. The axial lower limb injury tolerance value for the MiL-Lx was developed in a series of 18 cadaveric tests which, as mentioned previously, involved the removal of 90 mm of tibia in order to implant a load cell [5]. The introduction of a load cell to replace skeletal tissue is likely to have increased the risk of injury and potentially changed its mechanism. In addition, the fibula was left intact; it has been estimated that the fibula transfers 10-15% of the loading to the lower extremity [12]. Importantly, in both these experimental methods the sole of the foot was impacted, whereas in the experiments conducted here the foot was resting on the accelerating plate. It is likely that the feet of the occupants are in direct contact with the vehicle floor at the time of explosion. Therefore, it is likely that the boundary condition implemented here replicates the loading mechanism more accurately.

As anticipated there were differences in the force-time response of the MiL-Lx and Hybrid-III. The maximum load experienced by the Hybrid-III was greater than on the MiL-Lx, and the time to maximum load was longer in the MiL-lx. These trends have been observed previously [13]. This difference is likely to be due to the 70 mm compliant element in the MiL-Lx tibia.

The time to peak force for the ATDs and time to peak strain for the cadaveric specimens are in the same region, however, since the sample size is small statistical analysis to determine significance is not possible. On average, the combat boots in the Hybrid-III tests experienced 49.2% more compressive strain than in the MiL-Lx and 44.6% more compressive strain than the cadaveric tests. The behaviour of the combat boot under the MiL-Lx and cadaveric specimens was similar (within 3%). The large maximum compression of the combat boot under the Hybrid-III in comparison to cadavers and MiL-Lx indicates that its rigidity affects the behaviour of the boot beneath it. This result suggests that the Hybrid-III is likely not a suitable lower-limb surrogate if the effect of the combat boot on the lower limb is of interest. This finding must be taken into account when using the Hybrid-III to assess other similar mitigation technologies placed between the occupant's foot and the vehicle floor such as false floors, floor mats and blast-resistant seats.

V. CONCLUSIONS

This study compared the response of Hybrid-III, MiL-Lx and cadaveric lower limb specimens in a simulated under-vehicle explosion using a traumatic simulator in the laboratory. The load experienced by both the Hybrid-III and MiL-Lx was over the tolerances recommended by NATO [4]; however, no, or just minor, injury was seen in the 3 cadaveric tests. Although the samples size in this study is small, the results suggest that further investigation into the accuracy of the injury criteria for both surrogates is warranted. MiL-Lx and cadaveric tests resulted in the same amount of combat boot compression, whereas Hybrid-III tests resulted in a substantially greater boot compression. This finding suggests that the Hybrid-III is likely to be deviating from the response of the human limb in an under-vehicle explosion. Therefore future mitigation strategies based solely on Hybrid-III experiments are likely to be flawed.

VI. ACKNOWLEDGMENTS

The authors would like to express their appreciation to Northern Hydraulic Cylinder Engineers Ltd. for the construction of AnUBIS, and Warrant Officer Rachel Mackenzie MBE in Queen Elizabeth Hospital, Birmingham for operating the CT scanner out-of-office hours. The costs for the construction and design of the rig were covered by the Army Benevolent Fund (ABF) – The Soldiers' Charity; the Soldiers, Sailors, Airmen and Families Association (SSAFA) Forces Help; the FH Muirhead Charitable Trust; the Drummond Foundation; and the Defence, Science and Technology Laboratory (Dstl). The financial support of the Defence Medical Services (DMS) for AR, TJB, AMH, ATHW and JCC, of the Royal Centre for Defence Medicine (RCDM) for the acquisition of equipment and consumables, of BBSRC for NN, and of Dstl and ABF – The Soldiers' Charity for SDM are kindly acknowledged.

VII. REFERENCES

[1] Ramasamy A, Harrisson SE, Clasper JC, and Stewart MPM, Injuries from roadside improvised explosive devices, *The Journal of Trauma*, 65, 4, pages 910-914, 2008.

[2] Ramasamy A et.al, Blast-related fracture patterns: a forensic biomechanical approach, *Journal of The Royal Society Interface*, 8, 58, pages 689-698, 2011.

[3] North Atlantic Treaty Organisation HFM-090 TG 25, Test methodology for protection of vehicle occupants against anti-vehicular landmine and/or IED effects (HFM-090), 2007.

[4] North Atlantic Treaty Organisation HFM-148/RTG, Test methodology for protection of vehicle occupants against anti-vehicular landmine and/or IED effects, 2011.

[5] McKay B and Bir C, Lower extremity injury criteria for evaluating military vehicle occupant injury in underbelly blast events, *Stapp Car Crash Journal*, 53, pages 229-249, 2009.

[6] Yoganandan N, Pintar F, Boyton M, and Begeman P, Dynamic axial tolerance of the human foot-ankle complex, *Proceedings of 40th Stapp Car Crash Conference*, Albuquerque, New Mexico, USAA, pages 207-218, 1996.

[7] Bir C et.al, Validation of lower limb surrogates as injury assessment tools in floor impacts due to anti-vehicular land mines, *Military Medicine*, 173, 12, pages 1180-1184, 2008.

[8] McKay, BJ, Development of lower extremity injury criteria and biomechanical surrogate to evaluate military vehicle occupant injury during an explosive blast event, unpublished thesis (PhD), Wayne State University, Detroit, Michigan, USA, 2010.

[9] Ramasamy A et.al, In-vehicle extremity injuries from improvised explosive devices: current and future foci, *Philosophical Transactions of the Royal Society B: Biological Sciences*, 366, 1562, pages 160-170, 2011.

[10] North Atlantic Treaty Organisation AEP-55, Procedures for evaluating the protection level of logistic and light armoured vehicle: for mine threat, 2006.

[11] Bird R, Protection of vehicles against landmines, *Journal of Battlefield Technology*,4, 14-17, 2001.

[12] Moore KL and Agur AM, Essential clinical anatomy, Baltimore, MD, USA, Lippincott Williams & Wilkins, 2002.

[13] Pandelani T, Reinecke D, and Beetge F, In pursuit of vehicle landmine occupant protection: Evaluating the dynamic response characteristic of the military lower extremity leg (MiL-Lx) compared to the Hybrid III (HIII) lower leg, *Proceedings of CSIR 3rd Biennial Conference 2010*, CSIR International Convention Centre, Pretoria, South Africa, 2010.