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THE EVALUATION OF THE SOUTH AFRICAN SURROGATE LEG FOR LANDMINE PROTECTION INJURY MEASUREMENTS.

Bio-Mechanics

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ABSTRACT

For troop mobility and safety during peacekeeping operations, protection against landmines is key. Vehicle landmine protection validation testing is an integral part of military equipment procurement process and serves as an important technical evaluation baseline for protected vehicle research and development goals and outcomes. The aim of this study was to assess the ability of the South Africa (SA) surrogate leg to predict injuries due to rapid floor/ foot plate impacts in military vehicles subjected to anti-vehicle landmine explosions. Testing was conducted using the South African developed Lower Leg Impactor (LLI) generating five different loading conditions. However, only the two loading conditions with established PMHS force-time corridors are presented. These two conditions are for impacts with a peak velocity of 3.4 m/s and 5.7 m/s respectively. The results of the THOR-Lx leg, used to establish the correct loading regime, are also presented. Comparisons of force-time response show better correlation to the PMHS corridors for the THOR-Lx leg than for the SA surrogate leg. Additional testing to fully characterize the SA surrogate leg and future improvements are required and recommended if the objective of a bio-fidelic surrogate leg is to be met.

Keywords : Landmine Protected Vehicles (LPVs), Validation Testing, RSA-MIL-STD-37, STANAG 4569, AEP-55 Volume 2, Post Mortem Human Specimens (PMHS), South African (SA) Surrogate Leg, Lower Limb Impactor (LLI).

1. INTRODUCTION

Currently the South African peacekeeping forces are facing threats from first generation blast and Explosively Formed Projectile (EFP) mines under the belly of mine-protected vehicles. These mines are generally initiated by pressure fuses activated by loads of more than 200 kg from the vehicle’s wheels.

Anti-vehicular (AV) landmines and Improvised Explosive Devices (IEDs) are utilized to disable and destroy vehicles and to kill and injure the occupants. They present not only a threat to vehicle occupants during times of conflict, but their humanitarian impact extends into the future [1]. These explosive devices range in design, activation mechanism, and explosive power.

In the classical "underbelly blast" threat, the AV explosive devices are designed to detonate under the vehicle emitting an explosive shock wave followed by a rapidly expanding gas cloud containing detonation products and soil ejecta. The blast wave impacts the vehicle hull initially producing localized elastic and plastic floorboard deformation. The floorboard transmits high amplitude, short duration axial loads to the foot/ankle/tibia complex of the occupant. Depending on the size of the initial wave and its attenuation through armour, the axial loads may proceed to load the other regions of the body [2].

Prior to being deployed in the field, Landmine Protected Vehicles (LPVs) are validated against international standards such as RSA-MIL-STD-37 [3] or AEP-55 Volume 2 [4] using Anthropomorphic Test Devices (ATDs). The measurement data obtained from these instruments are processed and compared to various injury criteria to determine if the vehicle does provide sufficient levels of protection.

Studies conducted by experts in the field and through numerical studies, indicate that the lower leg is very vulnerable to injuries in AV landmine strikes [5]. Additionally the lower limb injury criteria are the most difficult for a protected vehicle to pass when it is validated for standard underbelly blast mine threats.

Due to the vulnerability of the lower extremities a SA surrogate leg was developed. Its objective was to provide a cheaper and more biofidelic alternative to a fully instrumented ATD to assess the landmine protection levels of protected vehicles [6]. This surrogate leg consists of a rigid frame with a single articulated lower limb attached centrally at the ‘hip’. This frame allows the leg to position firmly in standard seats and ensures that the total mass of the surrogate leg is around seventy five kilograms.

The SA Surrogate leg consists of a welded femur that attaches to a polypropylene tibia compliant element. A single channel axial load cell is attached between the tibia element and a simple ball ankle joint. A standard Robert Denton HIII foot is then attached to this joint. Additional tri-axial accelerometers and a face-on pressure transducer have been fitted to obtain additional human response data. The hip and knee joints are simple hinge joints [6].

Figure 1: Photograph of SA surrogate leg

The SA surrogate leg, costing roughly 5% of a fully instrumented ATD, has been extensively used in vehicle validation tests and research. It enables measured human response data to be obtained from high risk vehicle tests as well as enabling additional information to be gleaned from normal tests when using the ATD’s. However a number of anomalies and problems with the SA surrogate leg have been encountered.

The initial goal of this research is to evaluate the SA surrogate leg with respect to its bio fidelity as a potential for use in AV landmine evaluations. This data along with additional testing is required to meet the long term goal of upgrading the leg to better correlate to new published PMHS lower limb injury data.

The currently used AV landmine protection lower limb injury criterion [7] is recognised as being very conservative. This research has been based on using existing vehicle crash research instruments such as sled testers [8-9] which simulate frontal impact loads. These are generally lower than that generated by AV blast mines and are horizontal rather than vertical as for mines.

This has led to various recent research efforts regarding lower limb injuries and their prediction using the Hybrid III ATD with both the standard HIII and the THOR-Lx lower leg assemblies [10]. To date, two PMHS corridors based on typical AV mine loading conditions have been developed by WSU [10].

The research by WSU introduced five loading conditions and two PMHS response corridors for the lower extremities. The loading conditions were defined using the force time response of either a HIII or a THOR-Lx lower limb fitted to a standard HIII ATD placed horizontally as well as the impactor peak velocity. For loads higher than condition two, the THOR-Lx lower leg had to be used to validate the loading conditions as the HIII tibia load cell would be over loaded.

The THOR-Lx was developed to address short comings in the HIII ATD lower leg and to thus more realistically represent the human lower limb for frontal crash testing. It was developed both as part of the advance Thor crash test dummy as well as to be retrofitted to the 50th percentile HIII ATD.

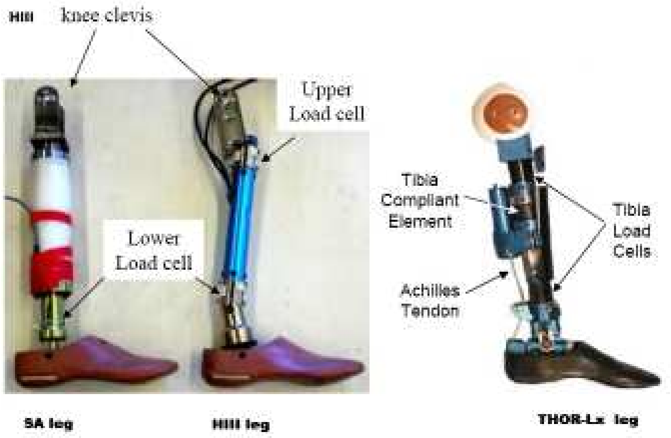

Figure 2: **SA surrogate, HIII and THOR-Lx legs**

Full scale mine testing of LPVs is too expensive to be used for research and development of occupant protection systems. Additionally, actual mine incident information is often classified, not available, or insufficiently detailed or documented. Thus to explore the effect of various parameters on the human response to AV landmine threat, cheaper repeatable testing methods are required.

This has led to the development of a number of methods to enable lower limb research to be executed in a laboratory. These are the Test Rig for Occupant Safety Systems (TROSS I™) [5], Defence R&D Canada air cannon [6], the Wayne State University tuned linear impactor [11] and the CSIR LLI [12]. There are other devices that have been built and used but data regarding these have not been published.

The Test Rig for Occupant Safety Systems (TROSS™) was developed to load a human surrogate with a force comparable to an AV blast mine detonated under a light military vehicle. This test apparatus consists of a membrane bottom plate. The footplate is loaded by scaled explosive charges under the bottom plate.

Figure 3: TROSS™ [13].

The Defence R&D Canada impactor consists of an air cannon that drives a piston and sled along a rail towards the target. Prior to impact, the piston is arrested and the sled, to which the impact face is mounted, is allowed to continue unassisted to impact the target. The impactor can allow for either a part of or the whole ATD to be used during testing.

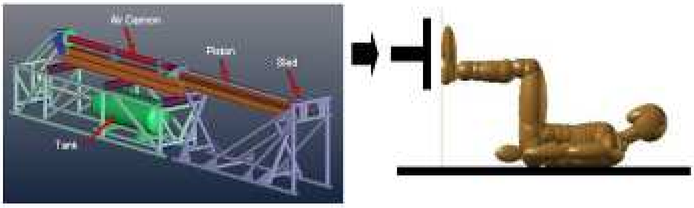

Figure 4: Air Cannon and Rail System setup [14].

The Wayne State University linear impactor uses an impactor that is tuned using an absorption material to obtain a loading profile. The impactor is driven by gas gun. The test method requires a completed

ATD to be positioned horizontally on its back. The centre of the heel of the foot of the impacted leg is aligned with the centre of the plate. This meant that the impact occurred straight through the shaft of the lower leg, which insured acceleration and force curves with a single peak.

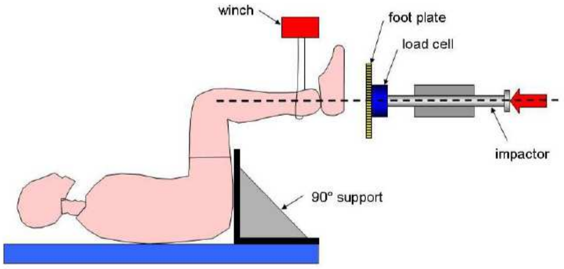

Figure 5: Linear Impactor test setup [10].

The LLI, developed by the CSIR [12] uses a steel plate that is driven by a compressed spring. The ATD is mounted in a vertical position over the impactor. The LLI can provide a maximum peak velocity of 7.2 m/s.

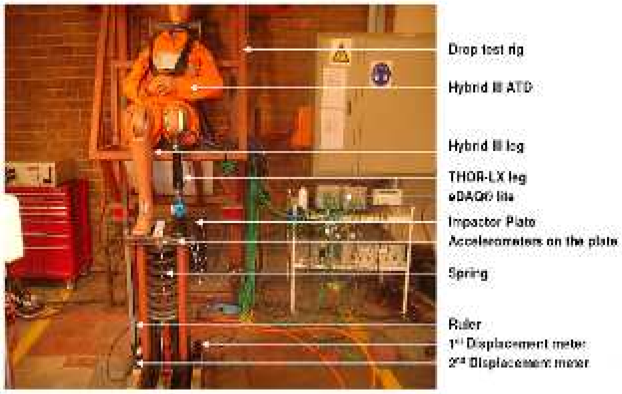

Figure 6: Experimental testing setup for testing with the LLI to simulate tibia loading.

The overall objective of this research is to characterise the SA surrogate leg when subjected to loading conditions simulating an AV blast mine strike. The next step is to compare the SA surrogate leg response against other available lower limb surrogate legs and to develop a dynamic model of the SA surrogate leg. Initial testing must be such to obtain sufficient dynamic data to refine and validate the dynamic model, and If required, to use this data to propose and implement changes to upgrade the SA surrogate leg to be compliant (biofidelic) both in terms of peak force and time duration to currently established corridors.

The objective of this paper is to present the initial evaluation of the response of the SA surrogate leg against recently published PMHS response corridors.

2. METHODOLOGY

Initial tests were based on ambient conditions and were focused on establishing the response of the SA surrogate leg to loading conditions II and III for which PMHS corridors have been published.

To evaluate the SA surrogate leg it is required that the force-time response be measured when the leg is subjected to loading conditions that closely approximate those used to develop the available PMHS response corridors. To obtain the required loading conditions II and II the CSIR developed LLI was used. This was achieved by tuning the LLI's peak velocity and evaluating the THOR-Lx's response to published data. The THOR-Lx was tested without the surrogate skin attached.

The surrogate leg under test was fitted to a 50th percentile HIII ATD. The ATD was installed on the CSIR drop test rig seat and positioned such that the foot was touching the LLI impactor plate with the spring fully extended. The seat was then locked in this position. The surrogate leg foot was positioned to be parallel to the impactor plate and the knee was maintained at a ninety degree angle to the tibia. The leg not being tested was positioned horizontally away from the impactor. No boots or socks were fitted for these tests. A total of 3 LLI tests were conducted for each surrogate for loading conditions II and III.

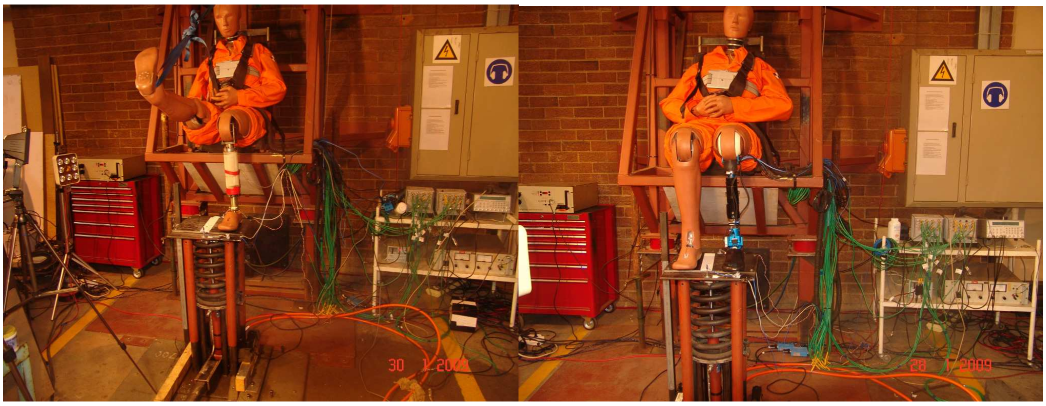

Figure 7: Hybrid III ATD with SA leg (left) and THOR-Lx leg (right).

Accelerometers were fitted to the impactor plate and laser displacement transducers were used to determine the velocity time profile of the impactor plate (Figure 6). High speed video was also taken. The data was processed in accordance with AEP 55 Volume 2 [4].

3. RESULTS

Since the corridors are only available for condition II and III without boot, only the force-time response from these two conditions are presented.

Set up results: WSU THOR-Lx vs. CSIR LLI THOR-Lx

Table 1: Comparison of WSU THOR-Lx and CSIR LLI THOR-Lx leg results

	WSU THOR-Lx Tibia Force (N) [13]	**LLI THOR-Lx Tibia Force(N)**
Condition 2	3845	3596
Condition 3	7316	6282

The THOR-Lx averaged lower tibia load was calculated at 3596 N, which fits within the bounds of the corridor constructed from normalized PMHS data for this corridor. The average duration also fits within the time range of the established corridor (Figure 8).

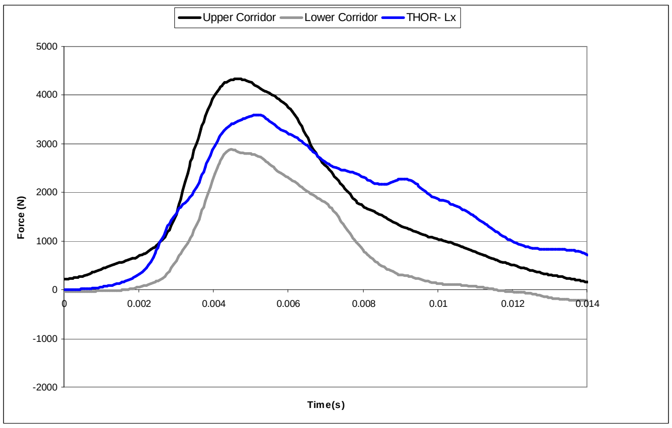

Figure 8: Response of CSIR LLI THOR-Lx leg compared to established corridor for condition II.

Testing with the THOR-Lx in condition III yielded an average peak force of 6282 N. This value is outside the range of the condition II corridor established by PMHS tests (Figure 9).

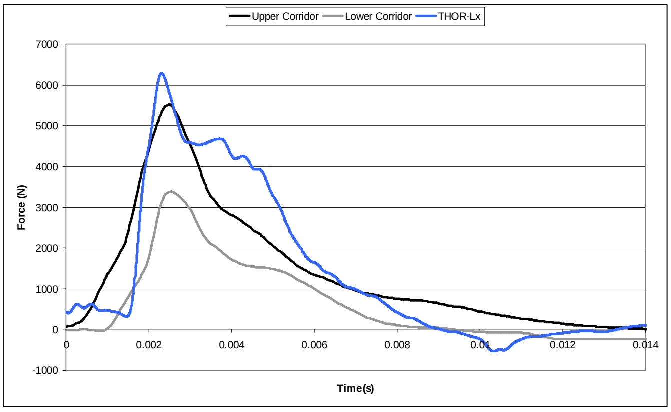

Figure 9: Response of CSIR LLI THOR-Lx leg in comparison to established corridor for condition III.

SA Leg Response Data CSIR LLI

Table 2: Results from SA leg testing with CSIR LLI

	LLI Tibia Force(N)
Condition 2	3596
Condition 3	24350

The average peak tibia force was 10916 N, which is 3.0 times more than the average peak tibia force measured in PMHS tests (Figure 10).

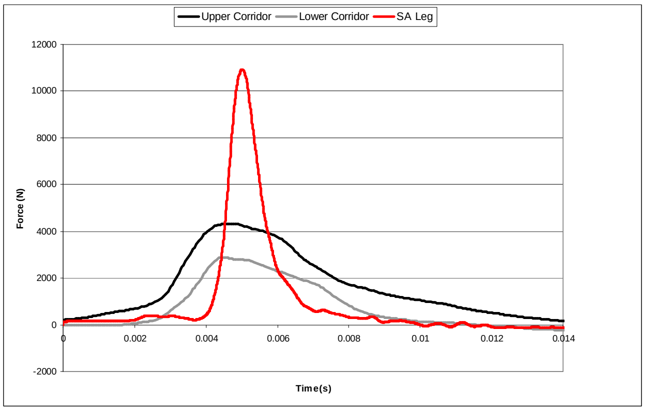

Figure 10: Response of SA surrogate leg compared to established corridor for condition II.

The SA surrogate leg measured an average peak tibia force of 24350 N (Figure 11) which is 5.5 times more than the average peak tibia force measured in PMHS testing.

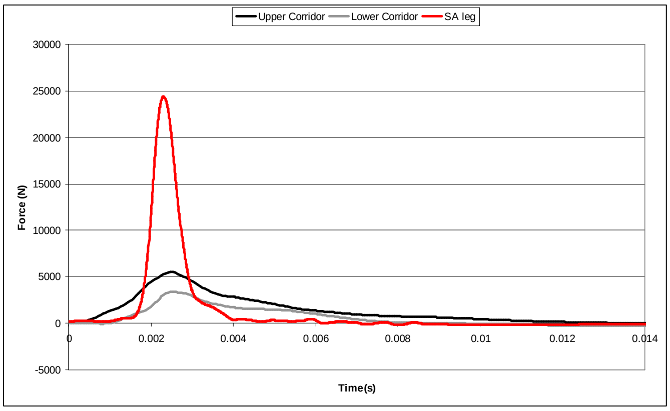

Figure 11: Response of SA surrogate leg compared to established corridor for condition III

4. DISCUSSION

It is seen that the LLI THOR-Lx response approximates the WSU response very well for condition II. For condition III, the LLI THOR-Lx response initially gives a very similar peak value however the second peak is much less prominent. It is thought that this response is due to the loading path differences in the experimental designs between WSU and the CSIR.

The SA surrogate leg exhibits a very similar trend to the simple and rigid steel tube HIII lower leg results [15] with a sharp peak that does not correspond at all to the PMHS corridors in both magnitude and duration. The SA surrogate leg however had excellent repeatability between various tests with the peak value varying by no more than 2 %.

This response is ascribed to strain rate effects with the higher loading rates resulting in increased stiffness of the polypropylene tibia element.

The force duration for the SA surrogate leg decreased with increased loading conditions. This trend was also present with the THOR- Lx. The duration decrease was proportional between the SA surrogate leg and the THOR-Lx leg. This trend is also ascribed to the increasing effects of strain rate on the material response.

5. CONCLUSIONS

The THOR-Lx measured similar forces and durations to those reported for the PMHS corridors for both conditions II and III. However, the Thor Lx started to over predict the peak value while still corresponding fairly well to the duration.

The SA surrogate leg measured forces which were higher with considerably shorter durations that did not match the general PMHS corridor trends. Additional testing is required to evaluate the SA surrogate leg under varying environmental conditions as well as additional testing to try and ascertain the source of the variability of the SA surrogate leg assembly.

Deviation in force measurements from the PMHS occurred due to the limits of the compressive elements within the surrogates, in comparison to the rate dependent modulus of elasticity bone. The THOR-Lx was originally designed to display this rate-dependant nature [15]; however, in the more severe explosive conditions (Loading condition III), it does not. There is a loss of biofidelity with both surrogates as the explosive load increases.

The THOR-Lx experiences tibia forces closer to those found in the PMHS testing due to the fact the THOR-Lx was designed as a more biofidelic version than the Hybrid III ATD surrogate leg. However, at higher loading, the THOR-Lx does not demonstrate a biofidelic response.

Further development and research is recommended for the upgrade of the SA surrogate leg as for both loading conditions it reacted less biofidelic than the THOR-Lx.

Follow-on work will include the evaluation of the newly developed MiL-Lx leg [16] specifically developed to assess AV landmine threats.

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REFERENCES

1. Geneva International Centre for Humanitarian Demining (GICHD). October 2004. *Humanitarian impact from mines other than anti-personnel mines*, Geneva.

2. B McKay and C Bir. 2008. *Development of a lower extremity injury criterion for military vehicle occupants involved in explosive blast events* (PASS).

3. S. Nell. 2000. Landmine protected wheeled vehicles: design, development and evaluation of, RSA-MIL-STD-37, Issue 3.

4. Procedures for Evaluating the Protection Level of Logistic and Light Armoured Vehicles, AEP-55 Volume 2 Edition 1, September 2006.

5. M. van der Horst, C. Simms, R. van Maasdam and P. Leerdam. 2005. *Occupant lower leg injury assessment in landmine detonations under a vehicle,* IUTAM Symposium on Biomechanics of Impact: From Fundamental Insights to Applications, Dublin, Ireland.

6. R. Dieterich. August 2003. *Foot ankle/complex detail design report,* KT528081, Issue.

7. N. Yoganandan, F. Pintar, M. Boynton, P. Begeman, P. Prasad, S. Kuppa, R. Morgan and R. Eppinger. 1996. Dynamic axial tolerance of the human foot-ankle complex, SAE 962426, USA: Society of Automotive Engineers.

8. S. Backaitis and H. Mertz. 1994. *Hybrid III: the first human-like crash test dummy,* SAE International, PT-44, USA.

9. M. Huang. 2002. *Vehicle Crash Mechanics,* CRC Press LLC, USA.

10. Barbir. 2005. Validation of lower limb surrogates as injury assessment tools in floor impacts due to anti-vehicular landmine explosions. Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science, Major: Biomedical Engineering (Impact Biomechanics), Graduate School of Wayne State University, Detroit, Michigan.

11. Manseau, J. and Keown, M. (2005c), *Evaluation of the complex lower leg (CLL) for its use in antivehicular mine testing applications*, In Proceedings of International conference of biomechanics of impact (IRCOBI), September, Prague, Czech Republic.

12. Whyte, T (2007) Investigation of Factors Affecting Surrogate Limb Measurements in the Testing of Landmine Protected Vehicles, Maters Thesis, University of Cape Town, SA.

13. C. Bir, A. Barbir, M. Wilhelm, M. van der Horst, F. Dosquet and G. Wolf. 2006. *Validation of lower limb surrogates as injury assessment tools in floor impacts due to antivehicular land mines*, IRCOBI Conference, Spain, Madrid.

14. M Keown. 2006, *Evaluation of surrogate legs under simulated AV loads*-Phase IV-,Report no R06-19, Biokinetics and associates Ltd.

15. Rudd R et al, Biofidelity Evaluation of Dynamic and Static Response Characteristics of the Thor Lx Dummy Lower Extremity, Journal of Crashworthiness pp 127-139;

16. http://www.dentontech.net/Products/page29/page29.html, last viewed on the 10/12/2009.