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The evaluation of MiL-Lx and Hybrid III Leg using Hybrid III and EUROSID2-re Anthropomorphic Test Devices

Thanyani Pandelani
CSIR Defence, Peace, Safety and Security
Pretoria, South Africa City, Country
tpandelani@csir.co.za

Abstract— **This paper presents the evaluation of the injury measurement response of the Hybrid III and ES2re ATD's using both the HIII and MiL-Lx instrumented lower legs as loaded by the Modified Lower Limb Impactor (MLLI).**

***Keywords*— MiL-Lx;STANAG 4569;AEP 55 Volume 3;EuroSID 2-re;Hybrid III**

INTRODUCTION

Most military research and procurement organizations utilize standard test methodologies for evaluating the protection level of military vehicles against kinetic energy, artillery, grenade, IED and mine blast threats. These methodologies standardize test conditions, define threat levels, describe measuring devices including, where applicable, Anthropometric Test Devices (ATDs), and specify required injury criteria and minimum injury acceptance levels.

The effectiveness of a protection system is determined by comparing the biomechanical response measured by the ATD to established human injury tolerances corresponding to the lower extremity surrogates used.

NATO affiliated military organizations typically qualify the protection levels of a vehicle to Standardization Agreement (STANAG) 4569 and related Allied Engineering Publications, Volume 2 for landmine and Volume 3 for IED protection. South Africa specifies landmine protection evaluation must comply with RSA-MIL-STD-37.

There are currently two ATDs specified for NATO and South African for military vehicle protection evaluation, these are the Humanetics fiftieth percentile Hybrid III and EuroSID2-re (ES2-re) ATD's. However the Hybrid III ATD was developed for frontal impacts in automotive crash testing. The ES2-re ATD is a side impact test device developed to evaluate occupant protection during lateral car impacts.

Experimental studies indicate that the lower leg is very vulnerable to injuries in landmine strikes [1] and accordingly this lower leg criterion tends to be the most difficult one to pass. The current landmine protection lower limb injury criterion specifies that the Hybrid III leg be used, but it is considered by many to be too conservative when applied to landmine protection evaluation [2].

This has resulted in various research efforts [3], [4] which culminated in the collaborative development of the Military Lower Extremity (MiL-Lx) leg by Wayne State University WSU and Humanetics (formerly Robert Denton) using the Hybrid III ATD. A risk curve based on tibia force and probability of injury was subsequently developed by Mckay [5].

The NATO AEP-55 Landmine and IED guidelines (Vol 2 Edition 2 and Vol 3 Edition 1), still to be formally published, allow the National Authority (NA) to use either the original Hybrid III (HIII) instrumented lower leg or the newly developed Mil-Lx lower leg on either the Hybrid III or the ES2-re ATD's.

The guidelines will now stipulate two critical injury thresholds for landmine protection evaluation. The threshold values are 2.6 kN for the Mil-Lx and 5.4 kN for HIII instrumented lower legs [4].

This value was determined by recording the load likely to result in a lower limb injury with an Ankle and Foot Injury Scales (AFIS). AFIS is divided into an injury severity and long term impairment scale. AFIS is a seven-point numerical rating system and evaluates a comprehensive list of lower limb injuries. AFIS also describes the relative severity (AFIS-S) and long term impairment (AFIS-I) [6].

The variation in mass, combined with the degrees of freedom between the Hybrid III and ES2-re ATD's poses a question as to whether the developed injury criteria will be accurately represented by the ES2-re when compared to the Hybrid III.

The objective of this paper is to present the experimental results to explain the discrepancies between the ATDs using both the HIII and MiL-Lx legs currently used to assess the operational fitness of military vehicles and their correlation to the response of the human lower limb.

EQUIPMENT AND METHODS

A. *Modified Lower Limb Impactor (MLLI)*

Conducting research in the field with explosives is both costly and time consuming. Explosives can only be used on specifically designated, regularly inspected testing ranges, adding to the inconvenience of their use. Methods of performing these tests in the laboratory without explosives vastly increase the yield of the research.

This led to the design of Lower Limb Impactor (LLI) [1]. The LLI is able to reach a peak velocity of only 7.2 m/s which, covers non-injurious and initial injurious corridors. However, it could not reach over-match loadings rates of WSU linear impactor of 10-12 m/s [5]. Wang et al [7] reported vehicle floor velocities from landmine blasts of over 12 m/s with duration less than 10 milliseconds.

The inability of the LLI to produce blast loading rates described by Wang et al [7] for landmine blast impacts resulted in the development of the Modified Lower Limb Impactor (MLLI).

The MLLI uses a spring powered plate that impacts the surrogate leg. The peak velocity of the plate is increased by increasing the compression of the spring (Figure 1). The ATD with the MiL-Lx and Hybrid III leg was positioned in an appropriate seat on the drop test rig.

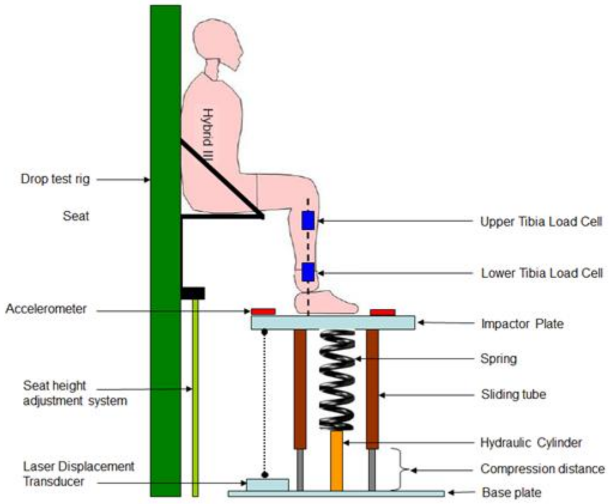

Figure 1: Modified Lower Limb Impactor (MLLI)

The MLLI impact plate and leg motion was captured using a Photron MH4 and APX video camera. The MH4 camera had four heads that were focussed on different areas of the test setup. The video was set to record at 2 000 fps. The Photron APX camera was set at 3,000 frames per second with a given resolution of 1024 by 1024 pixels.The LED, halogen and AC lights was used to provide additional light for the video footage. The Extech Easyview Light Meter was used to measure light level or illuminance which is the amount of light incident upon a surface area.

B. *Anthropomorphic Test Device (ATD's)*

1) *Hybrid III ATD*

The original Hybrid II family of ATDs was developed in 1972 by General Motors for assessment of restraint systems [8].This dummy proved to be a valuable tool in the evaluation of restraint systems and was recognized in official guidelines such as the Federal Motor Vehicle Standard 208 [8]. The Hybrid II remained the standard in automotive testing until the Hybrid III family of ATDs was introduced in 1987.

The Hybrid III addressed deficiencies of the Hybrid II, mainly in the area of the neck performance and provided improved bio-fidelity. The Hybrid III ATD also used a curved spine which better represented the occupant in a sitting position, as opposed to the original Hybrid II straight spine. The Hybrid III is still the standard in automotive crash testing; however, newer specialized ATDs are in development, which look to improve on the Hybrid III standard.

2) *EuroSID2-re (ES2-re) ATD*

The first EuroSID-1 (ES1) was developed according to the requirements of ECE R95 Regulation [9]. The ES1 had a number of known deficiencies including flat topping effect and that the seat frame could catch the dummy back plate during the initial phases of the impact, mitigating the rib deflections measured at the dummy.

The EuroSID-2 (ES2) was developed to address a number of known deficiencies of the ES1 dummy [10]. The design upgrades implemented in the ES2 ATD included a new thorax assembly and back plate design to reduce the flat topping effect and dummy-seat interference. The back plate was also re-designed, bringing it back inside the anthropometric shape of the human back and making it narrower and rounded to reduce the likelihood of grabbing.

The NHTSA experienced few occurrences of notable dummy-seat interaction in crabbed barrier testing, causing the agency to revisit the ES2 design. This led to the modification of the ES2 to ES2-re (with Rib Extensions). The ES2-re is a ES2 ATD with proposed modification to the rib unit, closing the space between the ribs and the spine [11].

C. *Lower extremity surrogates*

1) *Hybrid III Leg*

The Hybrid III (HIII) lower leg, sometimes called the Denton Leg, is part of the Hybrid III ATD original equipment (Figure 2). The HIII leg is, in principle, a steel tube which is connected to the knee via a fork at the top end and which has a simple ankle at the bottom end to which the foot is attached. The shaft of the tibia in the HIII leg is translated anteriorly at its proximal end and slightly posteriorly just above the ankle (see Figure 1). This creates angles between the ankle and knee areas of the tibia assembly. The HIII lower leg has no cushioning or equivalent elements except the foot elastomer and heel pad [12].

For instrumentation, the HIII lower leg contains both upper and lower tibia multi-axis load-cells capable of measuring moments and forces. Accelerometers can be mounted on the centre of the tibial shaft and the foot. An ankle load-cell positioned on top of the foot, just below the ankle joint, can also be fitted.

The currently used Anti-Vehicular (AV) landmine protection lower limb injury criterion [13] specifies that the HIII lower leg be used, but it is considered by many to be too conservative when applied to vehicular landmine protection evaluation.

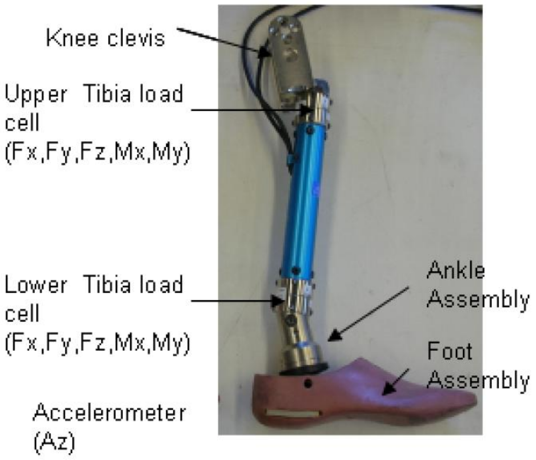

Figure 2: Hybrid III ATD Lower Leg [12]

2) Military Extremity Leg (MiL–Lx)

The limitations of the HIII leg resulted in various research [3], [4] efforts which culminated in the collaborative development of the MiL-Lx leg by WSU and Humanetics using the Hybrid III ATD. A risk curve based on tibia force and probability of injury was subsequently developed by [5]. The Mil-Lx leg measurement response (upper load cell) was validated by WSU using Post Morten Human Subjects (PMHS) data [5] for WSU loading condition 1 (WSU C1-7.2 m/s).The new leg design reflects a straight leg when compared to the existing HIII leg and has a compliant element as well as a simplified joint between the foot and tibia (Figure 3).

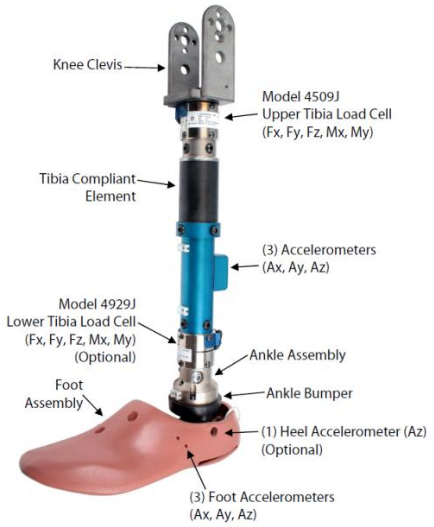

Figure 3: Military Extremity Leg (MiL–Lx) [1]

D. Test conditions

Mckay [14] established three incrementally severe experimental impact conditions. The impact conditions, termed WSU Condition 1, 2, and 3 (referred to as WSU C1, WSU C2, WSU C3), targeted an impacting floorplate velocity of 7.0, 10.0, and 12.0 m/s respectively (900, 1837, 2645 J). As illustrated in Figure 4, the range of floorplate velocity and kinetic energy furnished by Mckay and utilized in this study are similar. Furthermore, the upper floorplate velocity boundary of 12 m/s aligns with Wang et al. [7] who reported a medium sized armoured vehicle floorplate might exceed 12 m/s following an AV landmine underbelly blast.

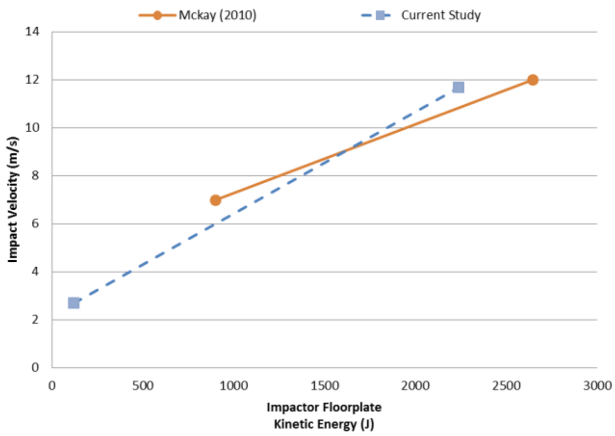

Figure 4: Comparison of Minimum and Maximum Loading Severities Utilized in Lower Extremity Injury Risk Models

Six incrementally severe experimental impact conditions were used in this study. The impact conditions, termed condition 1, 2, 3, 4, 5 and 6, (referred to as MLLI C1-C6) targeted an impacting plate velocity of 2.7, 3.4, 4.4, 5.7, 7.2 and 10.2 m/s respectively. The test condition was grouped into three categories namely low, medium and high severity impacts as shown in TABLE I.

TABLE I. IMPACT SEVERITY FOR THE MLLI

Test Condition	**Average Velocity (m/s)**	**Average Impactor KE (J)**
Low Severity Impact	2.7	119
	3.4	179
Medium Severity Impact	4.4	324
	5.7	532
High Severity Impact	7.2	851
	10.2	1682

RESULTS

The MiL-Lx and HIII leg were tested using the MLLI described in section A using the Hybrid HIII and ES2-re ATD. The new NATO standard [15] specifies the use of upper tibia load on the MiL-Lx while the use of lower tibia load cell on the HIII leg. The upper tibia load cell results on the MiL-Lx were compared to the lower tibia load cell on the HIII leg.

A. Hybrid III ATD

Impacts tests were conducted on the Hybrid ATD connected to the Mil-Lx and HIII leg surrogate to determine response of the surrogates under incrementally severe impact conditions. The comparison of the Mil-Lx leg with the HIII leg was done at ambient test conditions.

1) Hybrid III Leg

The response of the HIII leg tested at low severity impacts is shown in TABLE II.The axial load data were collected over a range of velocities (2.7 –3.4 m/s). The HIII leg does not allow for high input loads due to the rigid structure in combination with the allowed load range of the load cells thus the tests were limited to around 3.4 m/s peak impactor velocity.

TABLE II. FORCE MEASURED FROM THE HYBRID III LEG LOWER TIBIA LOAD CELL.

Test Condition	Average Velocity (m/s)	Impactor KE (J)	Average Peak LT Fz (N)	Std Dev LT Fz (N)	Probaility of AIS 2+ Injury
Low Severity Impact	2.7	119	7061	354	31%
	3.4	179	9801	403	80%

2) *MiL-Lx leg*

TABLE III shows the biomechanical response of the MiL-Lx leg upper tibia load cell. The axial load data were collected over a range of velocities (2.7 – 10.2 m/s). TABLE III compares the average biomechanical response of the MiL-Lx at each impact severity.

TABLE III. FORCE MEASURED FROM THE MIL-LX LEG UPPER TIBIA LOAD CELL.

Test Condition	Average Velocity (m/s)	Average Peak UT Fz (N)	Std Dev UT Fz (N)	Probaility of AFIS 4+ Injury
Low Severity Impact	2.7	1857	78	6%
	3.4	2480	24	9%
Medium Severity Impact	4.4	3307	94	15%
	5.7	3901	44	21%
High Severity Impact	7.2	5 154	137	37%
	10.2	7 843	203	78%

Figure 5 shows the biomechanical response of the HIII and MiL-Lx lower leg compared to the proposed injury risk criteria. The HIII lower tibia injury risk for the MLLI C1-C2 is 31 % and 80 % respectively. This represents a fail on the lower tibia. This trend suggested the HIII leg surrogate is rigid in comparison to a human lower limb. The MiL-Lx upper tibia injury risk for the C1-C2 is 6 and 9 % respectively.

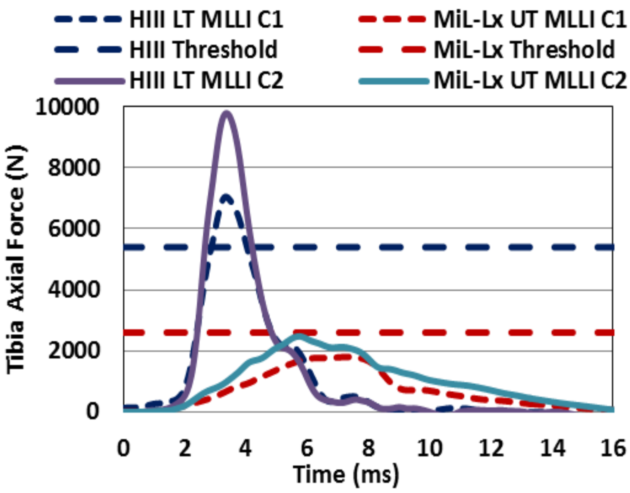

Figure 5: Comparison of Injury threshold of HIII Lower and MiL-Lx Upper Tibia forces (Fz) to MLLI Low Severity Impacts.

B. *EuroSID2-re (ES2-re) ATD*

The ES2-re was impacted fitted to the Mil-Lx and HIII leg surrogate to determine if this particular ATD was capable of distinguishing response of the surrogates different impact conditions.

1) *Hybrid III Leg*

The response of the HIII leg tested at low severity impacts is shown in TABLE IV. The axial load data were collected over a range of velocities (2.7 –3.4 m/s). As above, the HIII leg could not be tested at peak impactor velocity above 3.4 m/s.

TABLE IV. FORCE MEASURED FROM THE HYBRID III LEG LOWER TIBIA LOAD CELL.

Test Condition	Average Velocity (m/s)	Impactor KE (J)	Average Peak LT Fz (N)	Std Dev LT Fz (N)	Probaility of AIS 2+ Injury
Low Severity Impact	2.7	119	7599	18	42%
	3.4	179	10548	640	95%

2) *Mil lx leg*

TABLE V shows the biomechanical response of the MiL-Lx leg upper tibia tested at medium severity impact. The axial load data were collected over a range of velocities (2.7 – 10.2 m/s). The average peak upper tibia axial force for MLLI C1-C5 ranged from 1 944 N to 6 577 N.

TABLE V. FORCE MEASURED FROM THE MIL-LX LEG UPPER TIBIA LOAD CELL

Test Condition	Average Velocity(m/s)	Average Peak UT Fz (N)	Std Dev UT Fz (N)	Probaility of AFIS 4+ Injury
Low Severity Impact	2.7	1944	80	7%
	3.4	2237	36	8%
Medium Severity Impact	4.4	3172	73	14%
	5.7	3668	162	18%
High Severity Impact	7.2	4 820	185	32%
	10.2	6 577	124	61%

Figure 6 shows the biomechanical response of the HIII and MiL-Lx lower leg compared to the proposed injury risk criteria. The HIII lower tibia injury risk for the MLLI C1-C2 is 42 and 92 % respectively. This represents a fail on the lower tibia. The MiL-Lx upper tibia injury risk for the C1-C2 is 7 and 8 % respectively.

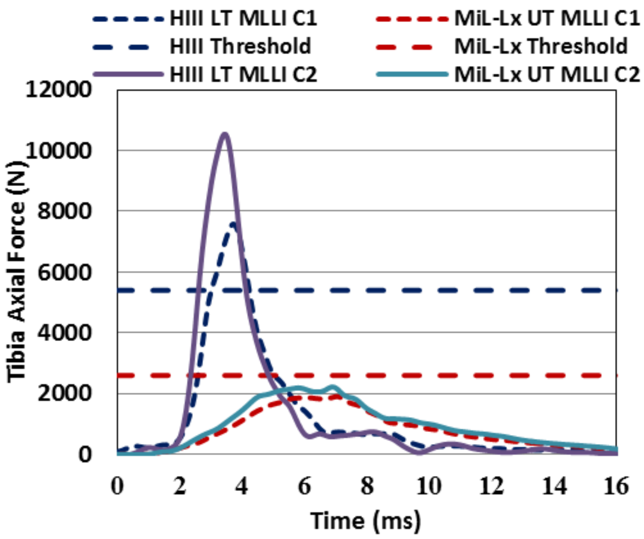

Figure 6: Comparison of Injury threshold of HIII Lower and MiL-Lx Upper Tibia forces (Fz) to MLLI Low Severity Impacts.

DISCUSSIONS

The HIII leg demonstrated high forces at relatively low impact velocities. The injury threshold of 5.4 kN was exceeded at an impact speed of 2.7 m/s for both the Hybrid III and ES2-re ATD. This implies that the HIII leg would have recorded a fail in accordance with Yoganandan's criterion for a 45 year old subject [13] . There is a slight difference in force measure with Hybrid III and ES2-re ATD using the HIII leg.

The MiL-Lx leg measured low forces at low impact velocities. The MiL-Lx only exceeded the injury threshold of 2.6 kN starting from an impact velocity of 4.4 m/s upwards. This implies that the MiL-Lx leg would have exceeded 10 % of AFIS 4+ accordance with McKay's criterion [5]. At highest impact severity, the Hybrid III ATD upper tibia force on the MiL-Lx starts to exceed significantly the force measure in ES2-re.

The results show that for all loading conditions, the HIII leg measures higher average upper tibia forces than the Mil-Lx leg with both the Hybrid III and ES2-re ATD. The HIII leg duration is considerably shorter than the MiL-Lx Leg. In addition, the HIII leg exhibits a larger variability than the Mil-Lx leg as the loading conditions increased. As above the HIII lower leg is a rigid tube with little compliance being given by the foot skin/heel pad thus the higher values are expected.

CONCLUSIONS

In general, the Mil-Lx upper tibia load cell measures peak forces that are considerably lower than that measured by the HIII lower leg. Due to force limitations on the HIII load cells, the maximum loading condition applied by the MLLI was with an impactor velocity of 3.4 m/s.

The Mil-Lx improves the accuracy and sensitivity needed to evaluate blast mitigation technologies designed to reduce injury to occupants of vehicles encountering Anti Vehicular landmines. By giving engineers the ability to assess and implement various countermeasures, occupant lower extremity injuries can be reduced or eliminated.

Although both the HIII and MiL-Lx legs are not perfect, there are fewer imperfections with the Mil-Lx. The MiL-Lx leg is more conservative and repeatable than the HIII leg. Also, the MiL-Lx leg has a strong correlation to the injury criterion and loading regimes for blast loading vertical impacts.

It is recommended that defence agencies and STANAG 4569 adopt both the Hybrid III and the ES2-re ATD with the MiL-Lx surrogate and replace the Hybrid III lower extremity for full-scale vehicle impact tests.

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