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# 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

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## Abstract

This study presents the results of a practical investigation into the robustness of the newly developed Military Extremity (MiL-Lx) lower leg, as compared to the Hybrid III (HIII) lower leg, with respect to repeatability and reproducibility under typical mine-protected vehicle landmine blast load conditions. Tests were performed using the Lower Limb Impactor (LLI) on both the MiL-Lx leg and the Hybrid III leg, and the relative responses compared. The results show that the MiL-Lx leg appears to be robust and reproducible, and not as much influenced by the addition of boots and angled impact than the Hybrid III leg.

## 1. Introduction

Anti-vehicular (AV) landmines and Improvised Explosive Devices (IEDs) are utilised to reduce the mobility of military and peace-keeping forces. AV landmines and IEDs are designed to damage or destroy vehicles, killing and injuring the occupants (GICHD, 2004; Manseau, 2005).

In the classical "underbelly blast" threat, the AV explosive devices are designed to detonate and emit explosive shock and blast loads on vehicles, which can impart extreme accelerations to the occupants (Bird, 2001). The blast wave that impacts the vehicle hull initially produces localised elastic and plastic deformation (Bir *et al.,* 2006).

This localised hull deformation can transmit high-amplitude, short-duration axial loads to the foot/ankle/tibia complex of the occupants. Depending on the size of the initial blast wave and its attenuation through armour, foot rests and other protection systems, the axial loads may proceed to load the other regions of the body (Bir *et al.,* 2008, McKay, 2008).

Experimental and numerical studies indicate that the lower leg is very vulnerable to injuries in AV landmine strikes (Gearts *et al.,* 2006). The currently used AV landmine protection lower limb injury criterion (Yoganandan *et al.,* 1996) specifies that the Hybrid III (HIII) leg be used, but it is considered by many to be too conservative when applied to vehicular landmine protection evaluation.

This assumption is partly due to a lack of correlation between injury models and the response of the HIII leg which is rigid. Although recent research has indicated that the 5.4 kN criterion could be valid for the AV mine loading regimes (McKay, 2009), the negative opinion of the existing criteria has recently led to various research efforts regarding lower limb injuries.

Research by the North Atlantic Treaty Organisation's (NATO) Human Factors and Medicine (HFM) Task Groups (TG) 025 and 148 investigated the responses of several lower leg surrogates subjected to typical AV mine loading conditions (NATO, 2007).

The Hybrid III (HIII) lower leg, sometimes called the Denton Leg, is part of the Hybrid III Anthropomorphic Test Device's (ATD) original equipment. 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 leg has no cushioning or equivalent elements except the foot elastomer and heel pad.

For instrumentation, the Hybrid III 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.

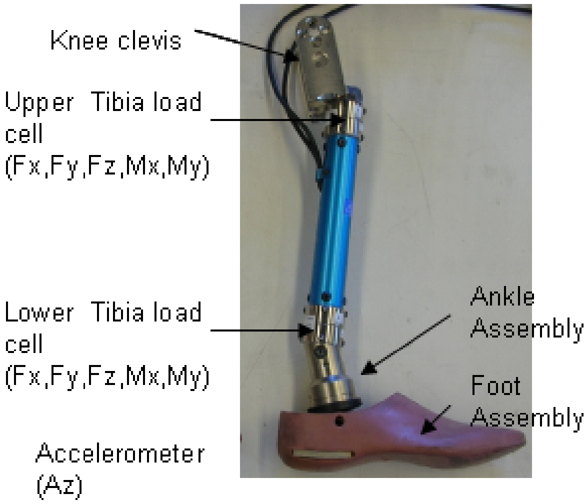

**Figure 1: Hybrid III (HIII) leg**

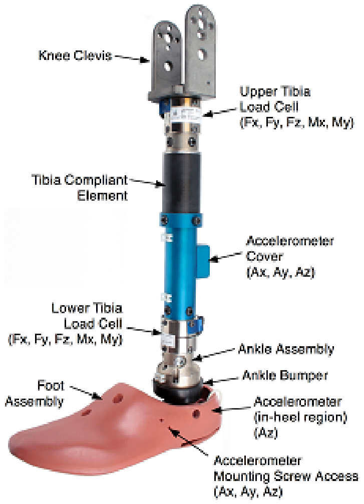

**Figure 2: Military Extremity Leg (MiL–Lx) (Dentontech, 2010)**

Based on the research outputs of HFM TG025 and 148, a new lower leg, the Military Extremity (MiL-Lx) leg (Figure 2), was developed collaboratively by Robert Denton and Wayne State University (WSU) using the WSU test methods and equipment. The development of the new surrogate leg was partly driven by the fact that the currently used Hybrid III leg's tibia load-cell saturated at extremely low, non-injurious velocity loading levels when compared to Post Mortem Human Surrogate (PMHS) test data.

The MiL-Lx leg was designed for impact loading of the foot for peak impact velocities of up to 7.2 m/s. The MiL-Lx leg is a straight leg design with compression-absorbing elements in the tibial shaft and heel and has been optimised for vertical forces and velocities. It is simple and robust (Dentontech, 2010). The MiL-Lx leg tibia design aligns the knee pivot, tibia and ankle pivot in a straight line by incorporating a straight knee clevis and straight ankle (www.dentontech.net). The MiL-Lx leg measurement response (upper load-cell only) was validated by WSU using PMHS data at an impact velocity of 7.2 m/s (McKay, 2009).

The purpose of this paper is to describe the results and evaluation methodology used to compare the MiL-Lx leg with the HIII leg. All test data were obtained using the CSIR-developed Lower Limb Impactor (LLI) (Whyte, 2007). The methodology comparing the new MiL-Lx surrogate leg, using the

LLI, is discussed in terms of the reproducibility, repeatability, sensitivity to angular impacts and the presence of boots.

## 2. Methodology

To investigate the MiL-Lx leg and the Hybrid III (HIII) leg measurement response, the MiL-Lx leg and the HIII leg were both tested on the LLI. The HIII leg does not allow high input loads due to the rigid structure in combination with the allowed load range of the load-cells. The comparison was therefore only done for conditions 1 and 2 with the LLI.

The evaluation of the measurement response of the two legs focused on comparing the reproducibility, the repeatability (including the effect of the surrogate skin), the effect of placing the leg Out of Position (OOP) and the effects of footwear.

The LLI 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. The initial foot position is determined by the normal free length position of the foot plate. The surrogate leg is held in position using a small wire while the impactor plate is withdrawn when the spring is hydraulically compressed. Only one leg is impacted at a time. The ATD is positioned vertically on the LLI (Figure 3) compared to the WSU horizontal positioning.

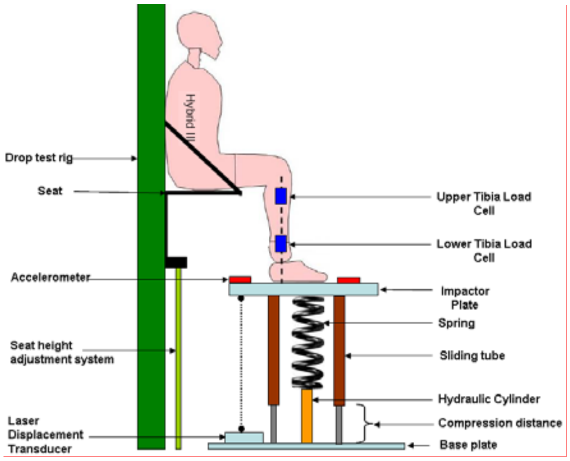

**Figure 3: Experimental set-up for the LLI (Pandelani *et al.,* 2010)**

The LLI uses laser displacement transducers to determine the peak plate or impactor velocity. The displacement data were filtered using a low-pass Butterworth filter at 1 000 Hz. The LLI also makes use of accelerometers mounted on the impactor plate to verify the velocity determined from the displacement transducers. The acceleration signal is integrated and compared to the calculated laser velocity measurements. The acceleration data were filtered using a CFC 1 000 filter (AEP-55, 2006). Tibia load data were filtered using a CFC 600 filter (AEP-55, 2006).

The LLI test methods also employ high-speed video to obtain additional data and the general mechanical response of the surrogate leg. For the LLI, the high-speed video was collected using a Photron Fastcam-APX RS model 250 KC at 3 000 frames per second with a given resolution of 1024 x 1024 pixels. All LLI data acquisition was conducted at 50 000 Hz using a SOMAT eDAQ Lite®.

The loading conditions for the LLI used for this series of tests are given in Table 1. Although a total of seven loading conditions ranging from 2.6 m/s to 10 m/s peak impact velocity were developed by NATO TG 025 and 148 (NATO, 2007), only conditions 1 and 2 were used. This is due to the higher loading conditions resulting in forces exceeding the normal operating capacity of the HIII load-cells.

**Table 1: LLI MiL-Lx and Hybrid III leg test loading conditions**

| Condition | CSIR LLI peak plate velocity (m/s) |
|---|---|
| C1 | 2.6 |
| C2 | 3.4 |

A 50th percentile male seated Hybrid III Anthropomorphic Test Device (ATD) was used for all these tests. Only a single leg was impacted during the test to maximise the momentum transfer of the LLI to the test specimen. The other ATD leg was lifted out of position during the test cycle. Both the HIII and MiL-Lx surrogate legs were fitted with a dedicated foot accelerometer and 6-channel upper and lower tibia load-cells. All leg comparisons are based on both the upper and lower tibia force time curves and average peak forces. The reason for this is that the MiL-Lx upper load-cell measurement is being proposed for the new lower limb injury criteria, whereas the current injury criteria for the HIII lower leg is based on the lower tibia load-cell.

## 2.1 Reproducibility

To investigate the effect of reproducibility on the force-time and average peak force response measurements, a series of incrementally increasing peak velocity tests were executed with LLI. The MiL-Lx and HIII lower leg measured and processed results were then simply compared to general shape and average peak force values.

## 2.2 Repeatability

For repeatability, each test point was executed three times. The repeatability was then evaluated using the peak measured value based on the standard deviation (SD) calculated from the processed test data. As with the loading method, the morphology of the force-time curve was visually inspected.

To further evaluate the repeatability, the tests were repeated on the LLI after the whole test programme was completed and the test rig decommissioned and then reassembled. As above, the results were then compared against the average peak force values and standard deviation, and a visual inspection was made of the processed force-time morphology. For completeness, the repeatability with the surrogate skin fitted was also evaluated.

## 2.3 Out of Position (OOP)

This is defined as any position where the foot/tibia angle and the femur/tibia angle are not at 90°. The 90° position was considered the base line. OOP is important as many vehicles incorporate foot rests to decouple the lower limb from the floor. To evaluate the influence of OOP, three different foot, tibia and femur angle combinations were tested. They were: (a) 45° foot/tibia angle with the femur/tibia angle maintained at 90°; (b) 45° foot/tibia angle and 135° tibia/femur angle; and (c) the foot horizontally positioned in relation to the impactor plate and the tibia/femur angle at 127°. These are presented in Figure 4. These OOP positions were chosen as they had been investigated previously (Horst, 2005).

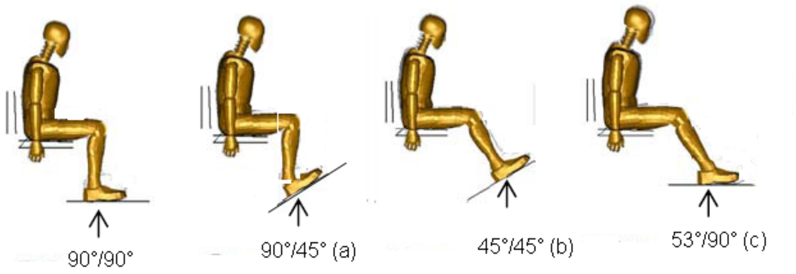

**Figure 4: Different test positions (Horst, 2005)**

The Revised Tibia Index (RTI) was calculated and compared for the MiL-Lx and the HIII legs. The injury risk curve for leg fracture using the RTI was developed by Kuppa *et al.*, (2001) and, although developed for the HIII lower leg only, was calculated for the MiL-Lx for comparative purposes.

## 2.4 Boot results

To evaluate the effects of boots on the upper and lower tibia response, the Canadian Defence Force desert boot was fitted on each leg and tested for each loading condition. The effect on average peak lower and upper tibia force as well as force-time morphology was compared.

# 3. Results

## 3.1 Reproducibility

The average lower tibia force results of both the MiL-Lx and HIII legs for condition 2 (C2) are presented in Figure 5 and tabulated in Table 3. As expected, from the data it can be seen that the MiL-Lx leg differs significantly from the HIII with respect to both duration and average peak value. The HIII leg exhibited shorter force durations than the MiL-Lx with durations of ±6 ms for the HIII and ±7.5 ms for the Mil-Lx.

The HIII lower leg recorded nearly double the average peak force on the lower tibia load-cell than the MiL-Lx leg at condition 1 (C1), and nearly three times the MiL-Lx at condition 2 (C2). This was expected as the HIII leg is a rigid tube assembly with limited energy absorption elements. Tests have shown that for these lower loading conditions the measured force loading rates and concurrence of peak force between the legs are similar; they start to differ markedly as loading conditions increase.

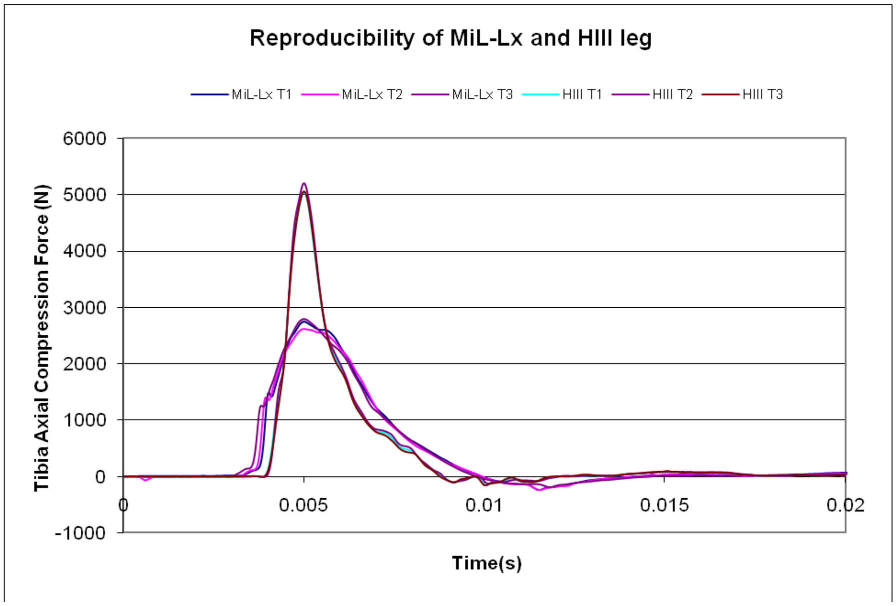

**Figure 5: Reproducibility of the MiL-Lx and HIII leg tested with the LLI**

## 3.2 Repeatability

For these tests, the MiL-Lx leg showed better repeatability results than the HIII leg, both with and without the leg skin fitted. The MiL-Lx leg had a standard deviation (SD) of less than 5% of the average peak value for all these tests as measured by the lower and upper load-cells (Table 2), whereas the HIII leg had more than 8% for C2. This high level of repeatability was also reflected when the MiL-Lx leg was tested with the surrogate skin fitted (Table 3). The MiL-Lx showed almost no difference when the skin was fitted, whereas the HIII leg gave significantly higher (±10% based on the lower tibia load-cell) average peak force values when the skin was fitted.

**Table 2: LLI ambient temperature results (without surrogate skin)**

| Impact angle | Test | Peak velocity (m/s) | MiL-Lx | | | | HIII | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | LT Average force (N) | SD (N) | UT Average force (N) | SD (N) | LT Average force (N) | SD (N) | UT Average force (N) | SD (N) |
| 90° | C1 | 2.6 | 2 717 | 85 | 2 537 | 78 | 5 100 | 83 | 4 012 | 86 |
| 90° | C2 | 3.4 | 3 287 | 44 | 3 020 | 135 | 10 381 | 290 | 8 506 | 756 |

**Table 3: LLI ambient temperature results (with surrogate skin)**

| Impact angle | Test | Peak velocity (m/s) | MiL-Lx | | | | HIII | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | LT Average force (N) | SD (N) | UT Average force (N) | SD (N) | LT Average force (N) | SD (N) | UT Average force (N) | SD (N) |
| 90° | C1 | 2.6 | 2 788 | 86 | 2 614 | 74 | 6165 | 536 | 4 410 | 585 |
| 90° | C2 | 3.4 | 3 304 | 47 | 3 246 | 137 | 11 124 | 261 | 8 698 | 196 |

## 3.3 Out of Position (OOP)

The MiL-Lx out of position responses for the lower and upper tibia average peak force results are presented in Table 4. It appears from the data that there is some degradation in repeatability of the results with the SD increasing for some positions for the MiL-Lx leg. This could be related to the experimental design, especially for the 90° angle.

Also surprisingly, the MiL-Lx leg gave higher readings for the 53º/90º tests than the 90º/90º tests for condition 2. The other test positions gave as expected lower average force readings than the 90º/90º tests. For comparison purposes, HIII data for two lower test conditions are presented in Table 4. In general, the HIII gives much higher values than the MiL-Lx leg for the 90º/90º tests as discussed above. This trend continues with the 53º/90º tests, but for the 90º/45º and 45º/45º tests, the HIII leg gave peak values only 20–30% higher than the MiL-Lx leg. In general this seems to indicate that the HIII leg is more sensitive to OOP than the Mil-Lx. This behaviour can be partly ascribed to the lower angled section of the HIII tibia and the rigid structure when compared to the relatively large flexible element in the MiL-Lx tibial tube.

**Table 4: LLI MiL-Lx leg and HIII leg out of position results**

| Loading condition | Foot position | Parameter | MiL-Lx leg | HIII leg |
|---|---|---|---|---|
| **C1** | **90°/45°** | Average LT Force (N) | 1 732 | 2 884 |
| | | Standard Deviation (N) | 516 | 36 |
| | | Average UT Force (N) | 1 596 | 2 431 |
| | | Standard Deviation (N) | 511 | 68 |
| **C2** | | Average LT Force (N) | 2 422 | 3 595 |
| | | Standard Deviation (N) | 463 | 120 |
| | | Average UT Force (N) | 2 207 | 2 940 |
| | | Standard Deviation (N) | 584 | 41 |
| **C1** | **45°/45°** | Average LT Force (N) | 1 738 | 1 807 |

| | | | | |
|---|---|---|---|---|
| | | Standard Deviation (N) | 23 | 39 |
| | | Average UT Force (N) | 1 655 | 1 555 |
| | | Standard Deviation (N) | 14 | 14 |
| **C2** | | Average LT Force (N) | 2 223 | 3 180 |
| | | Standard Deviation (N) | 39 | 413 |
| | | Average UT Force (N) | 2 131 | 2 588 |
| | | Standard Deviation (N) | 56 | 337 |
| **C1** | **53°/45°** | Average LT Force (N) | 2 193 | 4 718 |
| | | Standard Deviation (N) | 180 | 265 |
| | | Average UT Force (N) | 2 236 | 3 869 |
| | | Standard Deviation (N) | 186 | 206 |
| **C2** | | Average LT Force (N) | 3 211 | 8 963 |
| | | Standard Deviation (N) | 123 | 157 |
| | | Average UT Force (N) | 3 340 | 8 196 |
| | | Standard Deviation (N) | 67 | 121 |

The Revised Tibia Indices (RTI) calculated for the Military Extremity (MiL-Lx) leg and the Hybrid III (HIII) leg are presented in Table 5 and Table 6. The MiL-Lx calculated maximum RTI value is 0.71 for C2, which corresponds to an 8% probability of injury. The HIII leg calculated maximum RTI value is 1.94 for C2, which corresponds to a 99% probability of injury. Other than at the 90°/45° and 45°/45° test positions, the HIII leg gave considerably higher RTI values. It is suspected that these results are due to a combination of the angled and rigid structure of the HIII lower leg when compared to the straight geometry of the MiL-Lx leg and lower rotational stiffness due to the compliant element in the tibial shaft. It appears that the 45° impactor applies a reduced moment load to the lower limb surrogate.

**Table 5: MiL-Lx leg RTI results**

| Test | Peak velocity (m/s) | 90°/90° | 90°/45° | 45°/45° | 53°/90° |
|---|---|---|---|---|---|
| | | RTI | RTI | RTI | RTI |
| C1 | 2.6 | 0.26 | 0.50 | 0.31 | 0.34 |
| C2 | 3.4 | 0.38 | 0.71 | 0.38 | 0.55 |

**Table 6: HIII leg RTI results**

| Test | Peak velocity (m/s) | 90°/90° | 90°/45° | 45°/45° | 53°/90° |
|---|---|---|---|---|---|
| | | RTI | RTI | RTI | RTI |
| C1 | 2.6 | 0.68 | 0.40 | 0.28 | 1.00 |
| C2 | 3.4 | 1.50 | 0.63 | 0.44 | 1.94 |

### 3.4 Effects of foot wear (boot results)

The Lower Limb Impactor (LLI) boot test results for a peak floor impactor velocity of 3.4 m/s with the MiL-Lx and HIII legs are presented in Figure 6 below. As expected, the HIII leg lower and upper load-cell gave a significantly lower average peak force (± 20%) when a boot was fitted than without the boot, whereas the MiL-Lx gave almost no reduction in average peak force value. These results are to be expected as the HIII leg has almost no compliance, resulting in marked changes in peak forces measured when any form of compliance is introduced as with the addition of a boot. This effect is reduced when the surrogate leg already has significant compliance.

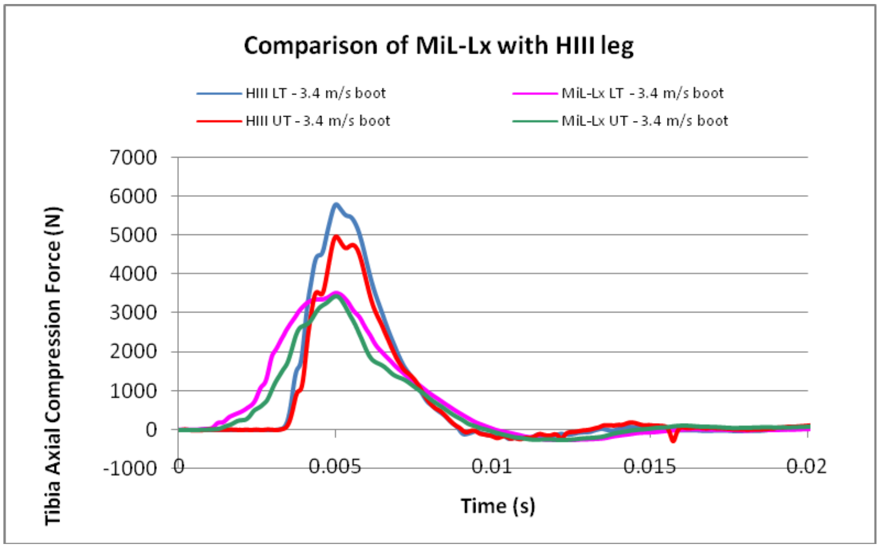

**Figure 6: LLI boot test results for peak floor velocity of 3.4 m/s**

## 4. Discussion

As expected, the Mil-Lx leg generates considerably different force-time and peak force measurements when compared to the HIII leg. This significant difference is primarily due to the large compliant element of the MiL-Lx leg. The MiL-Lx lower and upper tibia load-cells measure peak forces that are considerably lower than those measured by the HIII lower leg. Due to force limitations on the HIII load-cells, the maximum loading condition applied by the LLI was with an impactor speed of 3.4 m/s which produced a reading of over 8 kN on the HIII leg, while the MiL-Lx leg only measured a peak force of around 3 kN at the same impact velocity. The new heel pad also contributes to the overall lower dynamic response of the MiL-Lx leg.

The MiL-Lx repeatability was extremely good, with the standard deviation of all test points not varying more than 5% of the average peak force. This compares very well with the HIII leg, which had a standard deviation of more than 8% of peak force at an impact loading of only 3.4 m/s.

The MiL-Lx leg appears to be less insensitive to position changes whereas the HIII leg appears to have some sensitivity to OOP for certain position combinations. It is important to note that in general the MiL-Lx measures lower RTI values than the HIII, and could thus under-predict the possibility of lower limb injury. It must, however, be considered that the RTI was developed using the HIII leg and thus cannot be applied directly to the MiL-Lx measurements.

The MiL-Lx leg seems insensitive to the addition of boots. The HIII leg, due to its rigid structure, shows a large reduction in peak force measured when any form of compliant material is placed between the impact surface and the foot. This could result in the over-estimation of the protection levels offered by boots or other protection systems such as mats when using the HIII lower leg to evaluate their effects.

## 5. Conclusions

Based on the test results from this limited evaluation, the MiL-Lx leg appears to be a robust lower limb surrogate that can be subjected to considerably higher loading forces than the HIII lower leg. The MiL-Lx exhibits better repeatability characteristics than the HIII surrogate leg and is less sensitive to the addition of boots. This implies that the MiL-Lx is a more suitable surrogate to evaluate lower limb injuries than the HIII, when based on WSU (McKay, 2009) research, as this indicates injurious levels start with impactor loading speeds of 7.2 m/s.

However, for the MiL-Lx to be used as a lower limb surrogate, an injury probability distribution has to be developed. In addition, other existing injury criteria, such as the RTI, developed for the HIII surrogate leg, cannot be applied directly. Thus, if these criteria are important for landmine protection, additional research and testing are required to develop them for the MiL-Lx surrogate.

## 6. Acknowledgements

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