The Practical Evaluation of the Mil-Lx Lower Leg When Subjected To Simulated Vehicle Under Belly Blast Load Conditions

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Abstract: This study presents the initial results pertaining to a practical investigation into the robustness of the newly developed Military Extremity (MiL-Lx) lower leg, with respect to repeatability and reproducibility under typical mine-protected vehicle landmine blast load conditions. This evaluation was based on results obtained from two separate test rigs exhibiting different loading mechanisms, namely the Test Rig for Occupant Safety Systems (TROSS™) and the CSIR Lower Limb Impactor (LLI). The results show that the Mil-Lx lower leg appears to be robust and is less sensitive to loading method, temperature, Personal Protective Equipment (PPE) and position changes than other lower limb surrogates tested previously.

1. INTRODUCTION

Anti-vehicular (AV) landmines and Improvised Explosive Devices (IEDs) are utilized to reduce military and peace keeping forces' mobility. These devices disable and destroy vehicles, injuring and killing the occupants. They present not only a threat to vehicle occupants during times of conflict, but their humanitarian impact extends into the future [1, 2].

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 [3]. The blast wave that impacts the vehicle hull initially produces localized elastic and plastic deformation over the blast impact area. This localised 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 [4].

Experimental and numerical studies conducted by experts in the field, indicate that the lower leg is very vulnerable to injuries in AV landmine strikes [5].

The currently used AV landmine protection lower limb injury criterion [6] is considered by many to be too conservative when applied to vehicular landmine protection evaluation. This assumption is partly due to the criterion being based on vehicle crash durations rather than typical AV loading conditions, although recent research has indicated that the 5.4 kN criterion appears valid for the AV mine loading regimes [7]. This opinion has led to various recent research efforts regarding lower limb injuries.

Research by the North Atlantic Treaty Organisation's (NATO) Human Factors and Medicine (HFM) Task Group (TG) 025/148 investigated the measurement behaviour of several lower leg surrogates subjected to typical AV mine loading conditions [8]. The loading conditions used for these tests were developed and quantified using the TROSS™ system. This research effort was expanded to include Post Mortem Human Surrogate (PMHS) testing which has resulted in a new injury criteria being proposed [7]. The loading conditions for the TROSS™ and LLI used for this series of tests are given in Table 1.

Table 1: TROSS^{TM} and CSIR LLI Mil-Lx test loading conditions

Condition	TROSS^{TM} foot plate peak velocity (m/s)	CSIR LLI peak plate velocity(m/s)
1	1.5	2.6
2	3	3.4
3	4.1	4.7
4	5.1	5.7
5	8.8	7.2

Based on these studies, a new lower leg, the Mil-Lx leg (Figure 1), was developed collaboratively by Robert Denton using the Wayne State University (WSU) test methods and equipment. The development of the new surrogate was partly driven by the fact that the currently used Hybrid III (HIII) leg's tibia load cell saturated at extremely low, typically non-injurious velocity loading levels. The Mil-Lx leg measurement response (upper load cell) was validated by WSU using PMHS data [7] for WSU loading condition 1 (C1). The new leg design reflects a straight leg when compared to the existing HIII and has a compliant element as well as a simplified joint between the foot and tibia.

Figure 1: Military Extremity Leg (MiL–Lx) [9]

The objective of this paper is to describe the methodology of the test procedure and to compare the results obtained using the LLI for the Mil-Lx leg with the results using the TROSS^{TM} system. The methodology using the LLI is discussed in terms of the reproducibility, repeatability, effects of temperature, angular impacts and the presence of boots. A comparison of the response of the Mil-Lx leg to the HIII leg is also presented. The results that are obtained and used for the comparison are the tibia forces recorded by the legs.

2. METHODOLOGY

To evaluate the measurement response of the Mil –Lx leg, several areas were selected. These were loading method reproducibility, repeatability including the effect of the surrogate skin, Out of Position (OOP), temperature effects and the effects of the addition of PPE in the form of boots. The selection was based on available resources, facilities and issues considered important practical performance areas for a surrogate leg. Where feasible, the HIII lower leg was also tested for comparative purposes. For the Mil-Lx leg, only the upper load cell results are presented as this measurement has been proposed for the Mil-Lx injury criteria [7].

To investigate the Mil-Lx measurement response, two different Mil-Lx legs were tested on two separate test rigs, each using fundamentally different loading methods. These were the Test Rig for Occupant Safety Systems (TROSS ™) which was developed for blast tests by WTD 91 and IABG [10] and the spring driven CSIR Lower Limb Impactor (LLI) [11].

The TROSS™ system generates plate loading through the use of scaled charges that are detonated under a membrane plate (Figure 2). The charges are placed in a steel pot and no soil over burden is applied. The charges are scaled to provide specific membrane peak velocities. Both the surrogate legs were positioned on a platform that is directly mounted on the membrane plate.

Figure 2: TROSS ™ set up [12]

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. Only one leg is impacted at a time. The surrogate leg is held in position using a small wire while the impactor plate is withdrawn when the spring is hydraulically compressed. As with the TROSS™, the LLI positions the ATD vertically (Figure 3) compared to the WSU horizontal positioning.

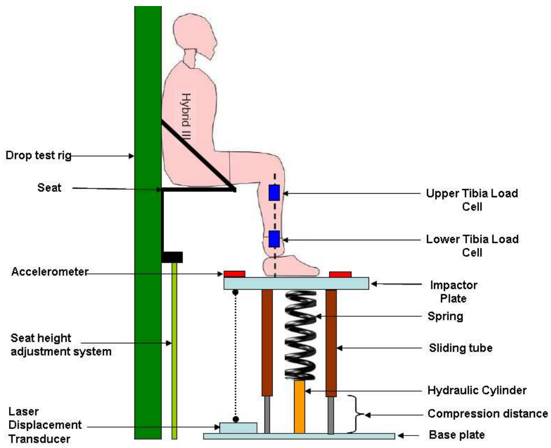

Figure 3: Experimental setup for the LLI

Both the LLI and the TROSS™ use laser displacement transducers to determine the peak plate / impactor velocity. The displacement data was filtered using a low pass Butterworth filter at 1000 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 was filtered using a CFC 1000 filter [12]. Tibia load data was filtered using a CFC 600 filter [12].

Both the TROSS™ and the LLI test methods also employ high speed video to obtain additional data and 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 by 1024 pixels. All LLI data acquisition was conducted at 50 000 Hz using a SOMAT Edaq Lite®.

2.1. Reproducibility

To investigate the effect of reproducibility on the peak force response measurements, a series of incrementally increasing peak velocity tests were executed with each of the two available test rigs.

Most of the tests were executed without the surrogate skin attached. This was done to better capture the various data required for the analysis of the dynamic responses of the surrogate legs using the high speed video. The measured and processed results were then simply compared with respect to general shape, peak value and duration against WSU supplied data.

2.2. Repeatability

To evaluate the repeatability, each test point was executed three times with the LLI and twice on the TROSS™. The repeatability was then evaluated using the averaged peak measured value and the standard deviation (SD) calculated from the processed test data. As with reproducibility, the morphology of the force-time curve was visually inspected. To further evaluate the repeatability, the ambient temperature tests were repeated on the LLI after the whole test program was completed and the test rig decommissioned and reassembled. As above, the results were then compared against the average values, standard deviation as well as visual inspection of the processed force time morphology. For completeness, the results using the surrogate skin were also evaluated.

2.3. Out of Position (OOP)

This is defined as any position where both the foot/tibia-impactor angle and the femur/tibia angle are not both 90°. This 90° position was considered the base line position. 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 impactor angle combinations were tested. They are: (a) 45° foot/tibia impactor angle with the femur/tibia angle maintained at 90°; (b) 45° foot/tibia impactor angle and 45° tibia/femur angle (as measured from the horizontal); and (c) the foot horizontally positioned in respect to the impactor plate (90º) and the tibia/femur angle at 53° (as measured from the horizontal). These are presented in Figure 4. These OOP positions were chosen as they had been investigated previously [12].

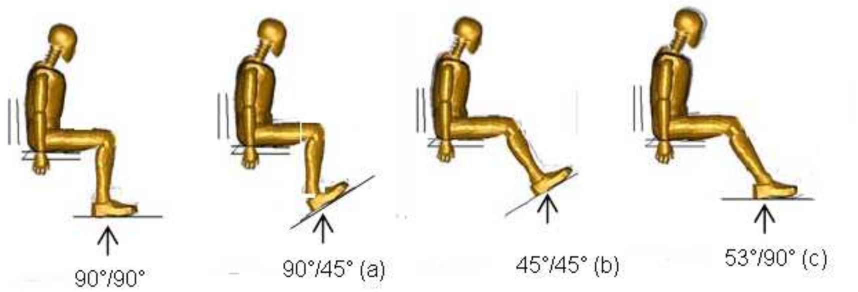

Figure 4: Different test positions [13]

2.4. Temperature:

To evaluate the effect of temperature, four test widely varying test points were chosen as field test conditions can vary considerably. These were -15ºC, 0ºC, ambient (15ºC) and 30ºC. Although the possibility of testing at -15ºC is improbable, it was included to ensure a wide enough temperature range. To achieve the required temperatures, the surrogate leg was removed from the ATD and conditioned in a laboratory chamber for 24 hours to enable sufficient time to achieve the required temperature. Due to time constraints, all the tests were executed as quickly as possible, however not all test points could be repeated. The processed upper tibia peak values were compared to each between the effect of temperature.

2.5. Effects of foot wear (Boot)

Previous tests had shown that a vast reduction in measured force can be obtained when a compliant boot is fitted to the HIII leg [14]. To evaluate the effect of boots, a series of incrementally increasing impact velocity tests were conducted. The processed peak lower tibia load was compared to evaluate the effect.

2.6. Comparison of MiL-Lx leg to HIII leg

A comparison of the Mil-Lx leg with the HIII leg was done at ambient test conditions. 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 comparative tests were limited to around 3 m/s peak impactor/plate velocity.

3. Mil-Lx RESULTS

3.1. Reproducibility

Due to blast loading limitations on the TROSS^{TM}, the TROSS^{TM} was unable to produce a 7.2 m/s peak floor velocity to enable a direct comparison of all three test methods. The average upper tibia force results for WSU and LLI 7.2 m/s peak impactor velocity are presented in Figure 5. In Figure 5, the TROSS^{TM} data corresponds to a 5.1 m/s floor peak velocity. From the data, it is evident that the LLI exhibits a steeper rise time than either the TROSS^{TM} or the WSU impactor. The LLI average force results are lower than that achieved by the WSU impactor. This is ascribed to the relatively heavier mass of the WSU impactor compared to the LLI impactor plate. Both the LLI and the TROSS^{TM} exhibited considerably shorter force durations than the WSU impactor with the LLI duration the shortest at 7.5 ms followed by the TROSS^{TM} with around 11 ms compared to the WSU results averaging around 13 ms.

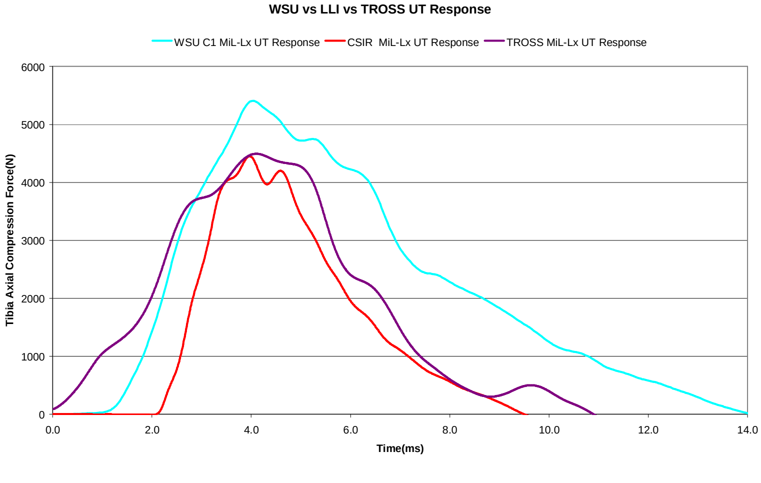

Figure 5: Comparison of WSU C1, CSIR LLI and TROSS^{TM} UT Fz

3.2. Repeatability

The LLI Mil-Lx average force gave good repeatability results with a standard deviation (SD) of less than 5% of the average peak value for all these tests as measured by the upper load cell (Table 2). This level of repeatability was also reflected when the Mil-Lx leg was tested with the surrogate skin fitted (Table 3). During the test series, the LLI was stripped down and later reassembled. The ambient temperature test series was repeated and the average upper tibia peak force results were mostly within 5% of the initial measured results (Table 4). The standard deviation was in the same range. The TROSS^{TM} repeatability based on two tests was similar to that achieved by the LLI. At higher levels, only one data set was available for the TROSS™ thus no average or standard deviation values are noted.

Table 2: TROSS™ and LLI Ambient Temperature Results (without boot)

Impact Angle	Test	LLI			TROSS™		
		Peak Velocity (m/s)	**UT Force (N)**	**SD (N)**	**Peak Velocity (m/s)**	**UT Force (N)**	**SD (N)**
90°	C1	2.6	2 537	78	1.5	1 288	144
90°	C2	3.4	3 020	135	3.0	2 328	123
90°	C3	4.7	3 332	178	4.1	-	-
90°	C4	5.7	4 018	141	5.1	4 494	-
90°	C5	7.2	4 452	112	8.8	8 393	-

Table 3: LLI (with surrogate skin) Ambient Temperature Results

Impact Angle	Test	LLI		
		Peak Velocity (m/s)	**UT Force (N)**	**SD (N)**
90°	C1	2.6	2 614	74
90°	C2	3.4	3 246	137
90°	C3	4.7	3 713	168
90°	C4	5.7	3 948	91
90°	C5	7.2	4 361	65

Table 4: LLI after reassembly Results

Impact Angle	Test	LLI		
		Peak Velocity (m/s)	**UT Force (N)**	**SD (N)**
90°	C1	2.6	2 451	80
90°	C2	3.4	2 902	122
90°	C3	4.7	3 022	139
90°	C4	5.7	3 798	175
90°	C5	7.2	4 556	151

3.3. Out of Position

The LLI Mil-Lx out of position response upper tibia average peak force results are presented in Table 5. 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.

Also surprisingly, the Mil-Lx leg gave higher readings for the 53º/90º tests than the 90º/90º tests for all tests other than condition 1. 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 is presented in Table 6. In general, the HIII gives much higher values (+200%) than the Mil-Lx leg for the 90º/90º tests (see Table 9). This is to be expected as the HIII leg is more rigid than the Mil-Lx leg. This trend continues with the 53º/90º tests, however, for the 90º/45º and 45º/45º tests, the HIII leg gave peak values that were only 20-30% higher than the Mil-Lx leg. This seems to indicate that the HIII leg is more sensitive to OOP than the Mil-Lx. Leg. This behaviour can be partly ascribed to the angled lower section of the HIII tibia.

Table 5: LLI Mil-Lx Leg Out of Position Results

Test	Peak Velocity (m/s)	90°/45°		45°/45°		53°/90°	
		UT Force (N)	SD (N)	UT Force (N)	SD (N)	UT Force (N)	SD (N)
C1	2.6	1 596	511	1 655	14	2 236	186
C2	3.4	2 207	584	2 131	56	3 340	67
C3	4.7	2 708	474	2 398	215	3 640	131
C4	5.7	3 674	181	2 670	42	4 211	166
C5	7.2	3 862	392	3 218	303	5 042	223

Table 6: LLI HIII Leg Out of Position Results

Test	Peak Velocity (m/s)	90°/45°		45°/45°		53°/90°	
		UT Force (N)	SD (N)	UT Force (N)	SD (N)	UT Force (N)	SD (N)
C1	2.6	2 431	68	1 555	14	3 869	206
C2	3.4	2 940	41	2 588	337	8 196	121

3.4. Temperature Effects

The average LLI Mil-Lx upper load cell peak force response to change in temperature is presented in Table 7. At -15ºC and 0ºC, only a single test was executed due to technical difficulties thus no standard deviation data is presented. From the results, the Mil-Lx leg appears to be insensitive to a wide temperature range with a maximum difference of no more than 15% of the average value being recorded over the 45ºC test range. The variability however seems to increase as the temperature is increased.

Table 7: LLI Mil-Lx Different Temperature Results

Test	-15°C		0°C		Ambient (15°C)		30°C	
	UT Force (N)	SD (N)	UT Force (N)	SD (N)	UT Force (N)	SD (N)	UT Force (N)	SD (N)
C1	2 178	-	2 389	-	2 537	78	2 257	174
C2	3 150	-	3 267	-	3 020	135	3 184	541
C3	3 805	-	3 334	-	3 332	178	3 713	219
C4	4 304	-	4 137	-	4 018	141	4 374	287
C5	4 500	-	4 952	-	4 452	112	5 192	428

3.5. Effects of Foot wear (Boot Results)

The TROSS^{TM} boot test results for a peak floor velocity of 3 m/s with the Mil-Lx and HIII legs are presented in Figure 5 below. All the LLI and TROSS^{TM} Mil-Lx average upper tibia force results with boot fitted are presented in Table 8. For the TROSS^{TM} tests, the HIII leg was tested in parallel with the Mil-Lx leg. As expected, the HIII leg upper load-cell gave a markedly lower reading when a boot was fitted than without the boot. The TROSS^{TM} and LLI Mil-Lx boot test results were variable with some readings being higher and others lower when a boot was fitted. The standard deviation increased in the LLI boot tests. Both the TROSS^{TM} and LLI results indicated that at lower impact velocities the effect of the boot was consistently to reduce average upper tibia force. This effect seemed to reduce and even increase loading as peak impactor velocity was increased. This effect could be due to increasing influence of the dynamic response of the various elements, such as boot mass, combined with strain rate effects of the leg components. The difference in response between the HIII and Mil-Lx legs appears to be due to the compliant element design of the Mil-Lx compared to the more rigid solid tube design of the HIII lower leg.

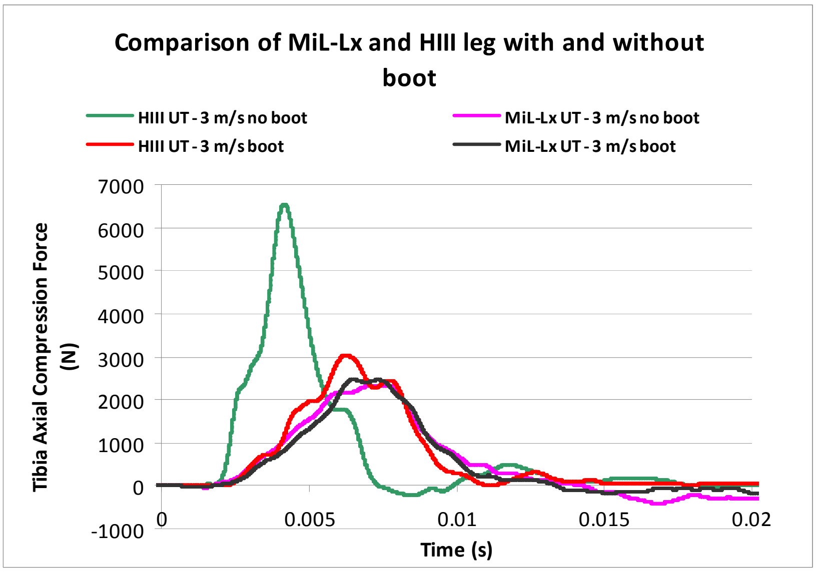

Figure 5: TROSS^{TM} Boot Test Results for Peak Floor Velocity of 3 m/s

Table 8: Mil-Lx Upper Tibia Average Force Test Results with Boots Fitted

Test	LLI			TROSS^{TM}		
	Peak Velocity (m/s)	UT Force (N)	SD (N)	Peak Velocity (m/s)	UT Force (N)	SD (N)
C1	2.6	1 983	28	1.5	1 113	12
C2	3.4	2 636	548	3.0	2 467	91
C3	4.7	3 426	326	4.1	3 314	65
C4	5.7	3 857	82	5.1	4 099	5
C5	7.2	4 651	220	8.8	10 910	-

3.6. Comparison of Mil-Lx leg to HIII leg

Table 9 shows a comparison of the maximum values of the lower tibia forces of the Mil-Lx and HIII leg. The results show that for all loading conditions, the HIII leg measures higher average upper tibia forces 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 upper load cell values are expected.

Table 9: LLI and TROSS^{TM} Mil-Lx leg and HIII Upper Tibia Fz Response Comparison Results

Test	LLI					TROSS^{TM}				
	Peak Velocity (m/s)	Mil-Lx		HIII		Peak Velocity (m/s)	Mil-Lx		HIII	
		UT Force (N)	SD (N)	UT Force (N)	SD (N)		UT Force (N)	SD (N)	UT Force (N)	SD (N)
C1	2.6	2 537	78	4 012	-	1.5	1 288	144	3 588	-
C2	3.4	3 020	135	8 506	-	3.0	2 328	123	6 456	-

4. DISCUSSION

The Mil-Lx leg gave reasonable reproducibility specifically when taking into account the differences in the test methods and the total loads applied. The maximum difference between the test methods was about 17% based on the maximum LLI impact velocity of 7.2. m/s. 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 also appears to be insensitive to position and temperature changes whereas the HIII leg appears to have some sensitivity to certain position combinations that result in drastically reduced peak forces being measured. The repeatability of the Mil-Lx leg does however appear to degrade up to 17% of the average peak force value for OOP tests.

With respect to clothing or PPE, the Mil-Lx leg again seems insensitive with respect to the addition of boots. No clear statement can be made regarding the Mil-Lx leg when boots are fitted as the results varied from reducing the upper load cell force to increasing the measurement as impactor/plate peak velocity increased. Additional investigation of this effect is required to understand fully this response. The Mil-Lx leg however is much less sensitive to the addition of boots than the HIII leg which 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 PPE or other protection systems such as mats, if the HIII leg is used.

Finally, 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 LLI was with an impactor speed of 3.4 m/s which produced a reading of over 8 kN while the Mil-Lx leg only gave a peak force of around 3 kN at the same impact velocity. This implies that the HIII leg would have recorded a fail in accordance with Yoganandan's criterion for a 45 year old subject [6].

5. CONCLUSIONS

The two Mil-Lx legs used in this test program were subjected to a total of 159 separate impact tests (LLI – 135 and TROSS – 24). No degradation in the Mil-Lx results was noticed. The Mil-Lx leg appears to be a robust surrogate leg that seems to be less sensitive to environmental factors, type of foot wear and positioning. Initial results show that the Mil-Lx leg can accommodate considerably higher loading regimes than the HIII leg.

The Mil-Lx leg appears to be relatively insensitive to environmental aspects, such as temperature changes, that are typically encountered when practically using such measurement equipment. The Mil-Lx leg gives very good repeatability in all applications tested.

The MiL-Lx leg is less sensitive to a change in boot type than the HIII leg. The rubber compliant element reduces the peak forces while increasing the force duration significantly when compared to the HIII leg.

For all conditions the Mil-Lx leg measures considerably lower average peak force than the HIII lower leg. However additional investigation is required to better understand the dynamic response of the Mil-Lx leg, in particular at higher loads.

Based on the limited tests executed on the LLI and TROSS™ systems, the Mil-Lx leg does not indicate any structural artefacts affecting the results and the leg appears robust as no damage or change in measurements over time was indicated. The Mil-Lx appears well suited for mine-protected vehicle protection validation tests as well as researching specific vehicular protection systems such as foot rests, boots and mats.

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