ATD Lower Leg Surrogate Selection and the Effects on the Evaluation of Blast Energy Attenuating Floor Mats

N. Shewchenko[1], E. Fournier[1], C. Quenneville[2]

[1]Biokinetics and Associates Ltd., 2470 Don Reid Drive, Ottawa, Ontario, Canada K1H 1E1, Shewchenko@biokinetics.com
[2]Liburdi Biomechanics Laboratory, Department of Mechanical Engineering and School of Biomedical Engineering, McMaster University, 1280 Main Street West, Hamilton, Ontario, Canada L8S 4L7

Abstract. Anti-vehicular landmine blasts cause rapid deformations of military vehicle hulls and floors, which pose substantial risk of injury to the lower legs. Loading to occupants can be assessed using an instrumented anthropomorphic test device (ATD), whose measurements can be compared to established injury criteria. NATO's AEP-55 STANAG 4569 recognises two surrogates for lower leg injury assessments: the rigid Hybrid III and the compliant Military Lower Extremity (MIL-Lx). The established injury criterion for the Hybrid III leg specifies a maximum lower tibia compressive load of 5.4 kN, whereas the MIL-Lx limit is 2.6 kN at the upper tibia. The assessment of load reduction provided by an Energy Attenuating (EA) floor mat may differ depending on the surrogate legs used. The difference in compliance between the two legs could affect the evaluation of these systems, resulting in an over- or under-estimation of the force attenuation. The responses of the two lower leg surrogates were evaluated at impact velocities up to 12 m/s, representing floor intrusions during anti-vehicle mine blasts. An air cannon was used to accelerate a rigid or padded floor plate into the sole of the surrogate lower legs, loading them axially, in order to assess the protective capability of a commercial EA floor mat. Comparisons of the surrogate legs' responses resulted in different evaluations of risk when compared to their respective injury criteria, with the Hybrid III leg exceeding its limit at an impact speed of 6.0 m/s, and the MIL-Lx exceeding its limit at 5.5 m/s. Furthermore, the inclusion of an EA mat had a greater protective effect on the Hybrid III than the MIL-Lx leg. These results indicate that these two surrogates are not equivalent in their assessment of protective capability. Therefore, the selection of ATD leg for testing of EA mats will influence the evaluation of these systems.

1. INTRODUCTION

Anti-vehicular (AV) landmine blasts cause rapid deformations of military vehicle hulls and floors. This poses a real and substantial risk of injury to the lower legs, which are frequently in direct contact with the floor. The rapid loading provided by floor deformations has previously been reported to reach accelerations and velocities on the order of 100 G and 12 m/s [12]. The safety of a vehicle is typically assessed through the use of an instrumented Anthropomorphic Test Device (ATD), measurements from which are compared to established injury criteria.

The most widely used ATD lower leg is the Hybrid III with an instrumented tibia (HIII; Humanetics Innovative Solutions, Plymouth, MI, USA) Figure 1. This lower leg surrogate attaches to the knee via an angled clevis, to which the tibia (a steel tube) mounts anteriorly, and is instrumented with upper (proximal) and lower (distal) tibia load cells. Previous studies have examined the response of the HIII lower leg to high speed impacts, and found it to be much stiffer than that of the natural leg, with axial forces reported to be between 1.8 and 2.8 times those recorded during tests of post mortem human subject (PMHS) specimens [1, 9, 2]. The impact velocity was noted in two of the studies to have a dramatic influence on the ATD:cadaver response ratio, with a closer representation being achieved under slower impact conditions and greater divergence for higher speed impacts [2, 9]. Additionally, the offset of the tibia's longitudinal axis from the knee and ankle has been noted to artificially induce bending moments under axial impact loading [10, 13].

To address the aforementioned issues, a new lower leg surrogate, the Military Lower Extremity (MIL-Lx, Humanetics Innovative Solutions, Plymouth, MI, USA) was developed, Figure 2. It consists of a straight knee clevis and tibia, and also has upper and lower tibia load cells. The integration of a compliant element in the tibia shaft adjacent to the upper load cell and the existence of a compliant heel pad provides dampening [4]. During its development, this leg was compared to PMHS data at an impact velocity of 7.2 m/s [4] and was determined to be more biofidelic than the HIII lower leg. In another study the tibia component (knee clevis and shaft) was evaluated over impact speeds of 2-7 m/s, and found to represent the natural human tibia very well ($R^2 = 0.83$) [10].

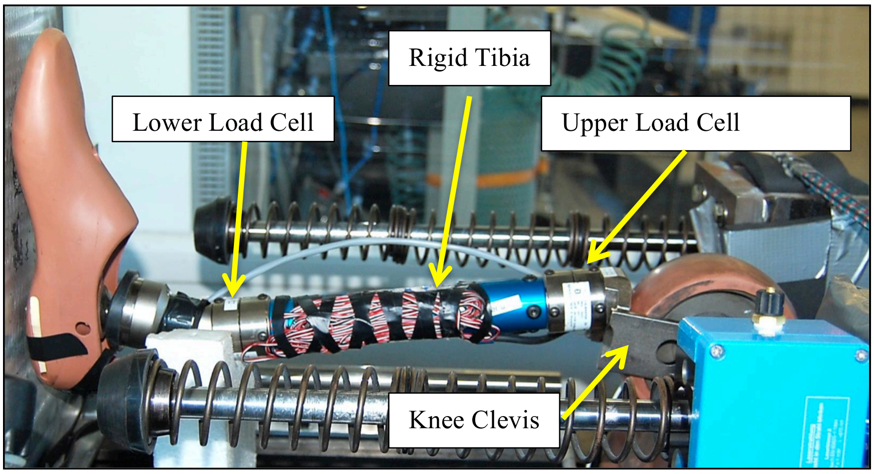

Figure 1. Hybrid III instrumented rigid lower leg.

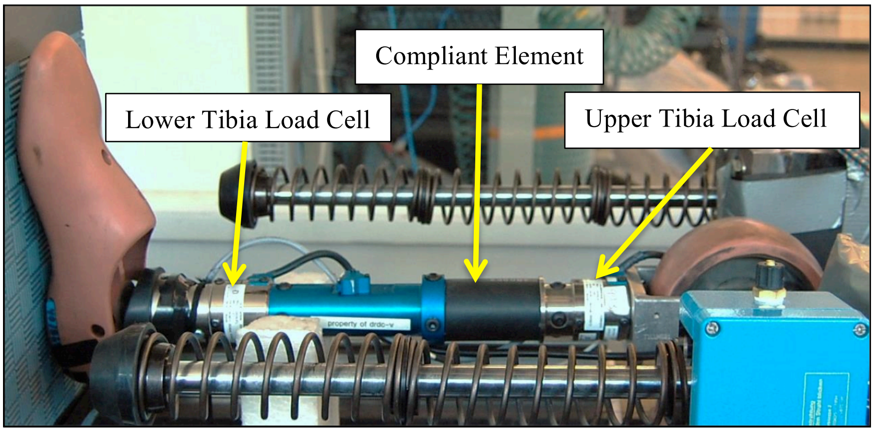

Figure 2. MIL-Lx compliant lower leg.

The current standard used by much of the defense community for injury assessment is the NATO AEP-55 STANAG 4569 (14). This document specifies the locations of measurement during blast testing, and the specific criteria which must be met. The previous release, issued in 2006, required the use of the Hybrid III ATD, equipped with a lower tibia load cell to record axial force (Fz), which is not to exceed 5.4 kN. The most recent release, issued in 2011, allows for the use of either the Hybrid III lower leg (with an injury threshold of 5.4 kN as measured at the lower tibia) or the MIL-Lx lower leg (with an injury threshold of 2.6 kN as measured at the upper tibia, to reflect the higher compliance of this surrogate) (14). As these surrogates are now being used interchangeably, their response to loading over the range of floor speeds that could possibly be encountered during under-body blast events (up to 12 m/s, [12]) must be properly characterized, as well as the effect of the different measurement locations and injury thresholds.

Energy Attenuating (EA) mats have received great attention from the defence community for their ability to reduce peak loads applied to the lower legs. These materials typically alter the shape of the pulse applied to occupants' lower legs by extending the duration and reducing the magnitude of loading. The protective (*i.e.,* force-reducing) capacity of several EA floor mats has been evaluated in a previous study using the Hybrid III lower leg, over speeds of 2-7 m/s [11]. In that study, Skydex® (Skydex Technologies, Centennial, CO, USA) reduced the peak axial force in the lower tibia load cell by 44% at 3 m/s, and by 74% at 7 m/s. The increased protection at higher speeds suggests that for the higher speeds of interest in the present study, Skydex® may provide optimal protection to the lower legs and warrants further investigation. As ATDs are typically used to quantify the capabilities of EA mats, the increased compliance of the MIL-Lx could affect the evaluation of these protective systems. This could alter assessments of the quality of products, and over or under-estimations of the force attenuation provided.

The purpose of this study was: 1) To evaluate the response of these two surrogates to impacts over a wide range of velocities representing loading from anti-vehicle mine blasts, 2) to quantify the protective (*i.e.,* force-reducing) capabilities of a commercial Energy Attenuating floor mat, and 3) to assess whether the selection of surrogate affects the evaluation of this floor mat.

2. METHODS

Impact tests were conducted with both a Hybrid III ATD lower leg (Humanetics Innovative Solutions, Plymouth, MI, USA) and a MIL-Lx ATD lower leg (Humanetics Innovative Solutions, Plymouth, MI, USA). The Hybrid III was fitted with a 5-axis upper tibia load cell (RA Denton Model No. 3643) and lower tibia load cell (RA Denton Model No. 3644) while the MIL-Lx was fitted with an upper tibia load cell (RA Denton Model No. 4509-JFL) and lower tibia load cell (RA Denton Model No. 4929-JFL). During testing, each leg was mounted at the knee to a Hybrid III ATD, the pelvis of which was securely attached to the rigid base of the testing apparatus (Figure 3). The ATD, lying on its back, was positioned to be with the upper leg vertical and lower leg horizontal. This allowed the application of axial loading horizontally to simulate the vertical motion of a vehicle floor during an AV mine blast event. The effect of anchoring the pelvic structure was determined to be insignificant as load transmission to the pelvis was found to occur well after maximal loading on the leg structure was reached.

A modified air cannon was used to accelerate a horizontally guided, 37 kg impactor (representing the floor pan of a vehicle), which struck the sole of the ATD foot simulating the loading employed by McKay and Bir in their validation of the MIL-Lx (15). The mass is also representative of the effective mass on the floor membrane of the German blast Test Rig for Occupant Safety Systems (TROSS) which was developed to conduct scaled detonations simulating floor pan loading to the lower leg during full-scale testing (16).

The impactor was driven by a sabot and piston arrangement. Prior to contact with the ATD foot the sabot was arrested preventing pressurized air from the air cannon nozzle from continuing to drive the impactor. Thus, the impactor was in guided free flight immediately prior to contact with the foot. After contact with the foot, the impactor was arrested by two hydraulic shock absorbers to control the contact duration and load transfer to the foot.

For each test, the ATD foot was positioned such that at contact its sole lay flat against the impactor's foot plate and the axis passing through the centre of the knee and ankle joint was perpendicular to the flat impacting surface. The legs were not restrained in any way, so as to allow realistic motion post- impact.

The impactor was instrumented with an Endevco 7264B accelerometer located on the rear surface of the impact face directly opposite the point of contact with the foot. The velocity of the impactor mass/footplate was measured immediately prior to contact with the foot using a fibre optic light gate (Biokinetics Light Gate). During the event, the displacement of the moving impactor was measured using a Micro-Epsilon LD 1627 laser displacement measurement sensor sampling at 20 kHz.

Load cell data were conditioned with Endevco Model 136 Amplifiers while data collection was performed with a National Instruments Model 6259 with 1000 Hz anti-aliasing filtering and data sampling conducted at 20 kHz.

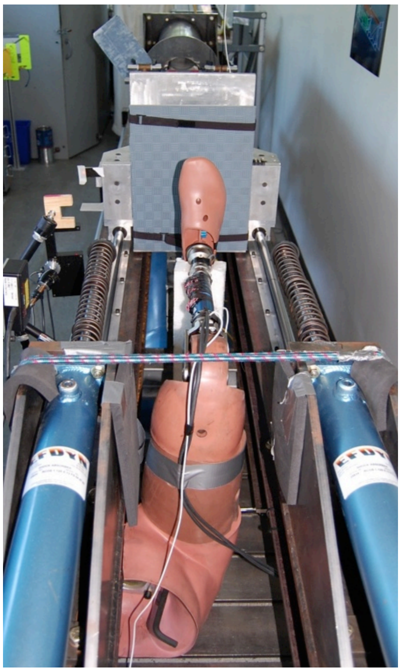

Figure 3. Test setup including the air cannon and leg assembly.

Loads were applied to the ATD in increasing magnitude over the range of velocities permitted by the capacity of the load cells (*i.e.,* up to 12 kN). To further evaluate the response of the legs over a wider range of impact velocities, an energy attenuating (EA) floor mat (Skydex®, Skydex Technologies, Centennial, CO, USA) was placed between the foot of the ATD and the plate. The legs were again tested over the velocity range permitted by the ATD load cells. A new sample of the EA mat was used for each impact test to eliminate any potential accumulated damage effects.

Three tests on each leg in the unprotected (no EA mat) condition were conducted at the beginning and end of testing at an average speed of 3.2 m/s for the Hybrid III and 5.4 m/s for the MIL-Lx. The pre- and post- test axial force values were analyzed using a one-way ANOVA ($\alpha = 0.05$) to evaluate the repeatability of the testing apparatus and any accumulation of damage over the course of testing.

3. RESULTS

The unpadded (no EA mat) Hybrid III leg was tested at impact velocities ranging from 2.24 – 4.89 m/s, and the unpadded MIL-Lx leg was tested at velocities from 3.19 – 11.66 m/s. The padded (with EA mat) Hybrid III leg was tested at velocities ranging from 4.55 – 9.13 m/s, and the padded MIL-Lx leg at velocities from 4.42 – 11.69 m/s. Typical temporal data for the load cells are presented in Figure 4a and Figure 4b at the 3.29 m/s and 5.46 m/s conditions for the Hybrid III and MIL-Lx, respectively. Peak load cell responses for the various conditions are presented in Figure 5a and Figure 5b for the Hybrid III and MIL-Lx, respectively.

The repeated trials had less than a 2% standard deviation from the average impact velocity, and an axial force standard deviation that was less than 5% of the average. There was no difference between the pre-test and post-test trials of the Hybrid III ($p > 0.43$), but there was a difference for the MIL-Lx at the upper load cell ($p = 0.04$; $p = 0.08$ for lower load cell).

For a given impact velocity, the Hybrid III lower load cell measured the greatest axial force, followed by the Hybrid III upper load cell, the MIL-Lx lower load cell, and the MIL-Lx upper load cell. The axial force in each load cell was highly linear for both legs in both the padded ($R^2 > 0.98$) and unpadded ($R^2 > 0.96$) conditions. At an impact speed of 2.8 m/s in the unpadded condition the Hybrid III leg's response exceeded the injury limit of 5.4 kN (measured at the lower load cell) and, similarly, the force injury threshold was exceeded at an impact speed of 6.0 m/s for the padded condition. The MIL-Lx leg exceeded the injury limit of 2.6 kN (measured at the upper load cell) at impact speeds of 4.4 m/s and 5.5 m/s for the unpadded and padded conditions, respectively.

To examine the influence of the padding on leg response, the ratio of padded to unpadded forces for given velocities was calculated (Figure 6). The inclusion of padding influenced the Hybrid III response the greatest, with axial forces between 17 – 34% of the unpadded condition. Furthermore, the force-reducing effect was velocity-dependent, with the greatest reduction in force occurring at low velocities and minimal difference between the upper and lower load cells.

Tests on the MIL-Lx in the padded condition resulted in axial forces that were between 67 – 89% of the unpadded condition. The upper load cell response was velocity dependent, with the greatest reduction in force (*i.e.,* most protection) observed at low impact speeds. The lower load cell showed the least velocity-dependency, with a slight increase in protection at higher impact speeds.

The resultant moments at each load cell were calculated for each impact test (Figure 7). The Hybrid III leg had a highly linear moment response with increasing velocity for both the padded ($R^2 > 0.94$) and unpadded ($R^2 > 0.95$) conditions, with the greatest moments occurring at the upper load cell. The MIL-Lx leg also had a linear moment response with increasing velocity for both the padded ($R^2 > 0.88$) and unpadded ($R^2 > 0.71$) conditions. For the unpadded condition, the MIL-Lx upper load cell consistently experienced greater moments than the lower load cell, but this trend was not observed in the padded condition, where resulting moments overlapped.

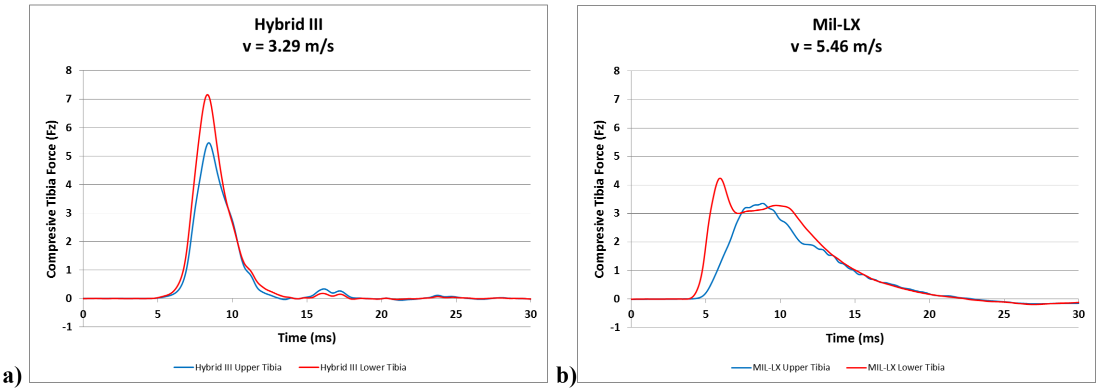

Figure 4. Axial forces for; a) the Hybrid III at 3.2 m/s, and; b) the MIL-Lx ATD lower leg at 5.4 m/s.

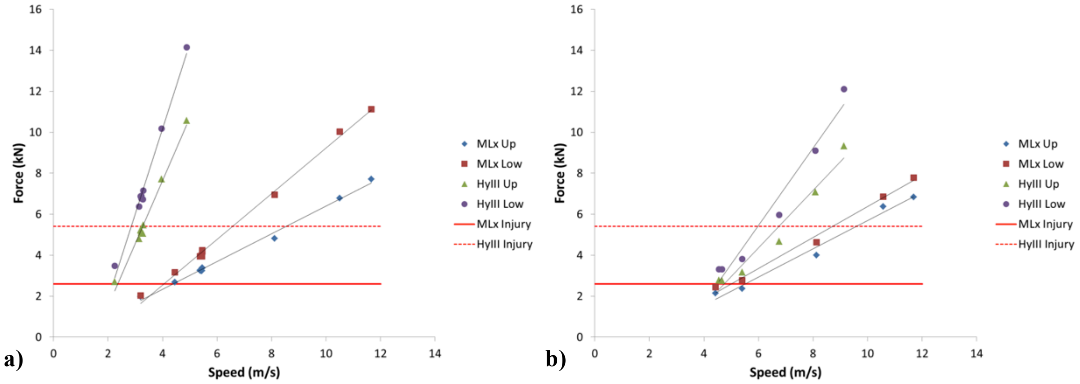

Figure 5. Peak axial force measurements for Hybrid III (HIII) and MIL-Lx (MLx) ATD lower legs; a) unpadded condition, and; b) padded (with EA mat) condition.

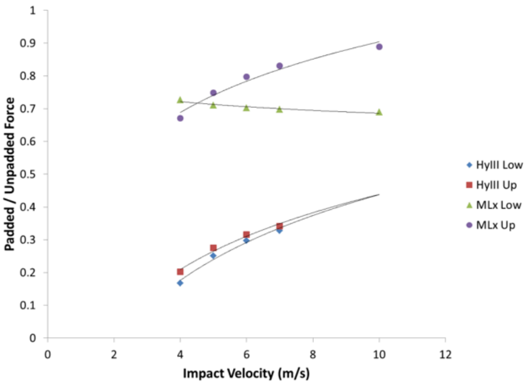

Figure 6. Ratio of axial forces for padded and unpadded conditions for the Hybrid III (HIII) and MIL-Lx (MLx) ATD lower legs. Lower values indicate greater protection provided by the EA mat (*i.e.,* a greater reduction in force).

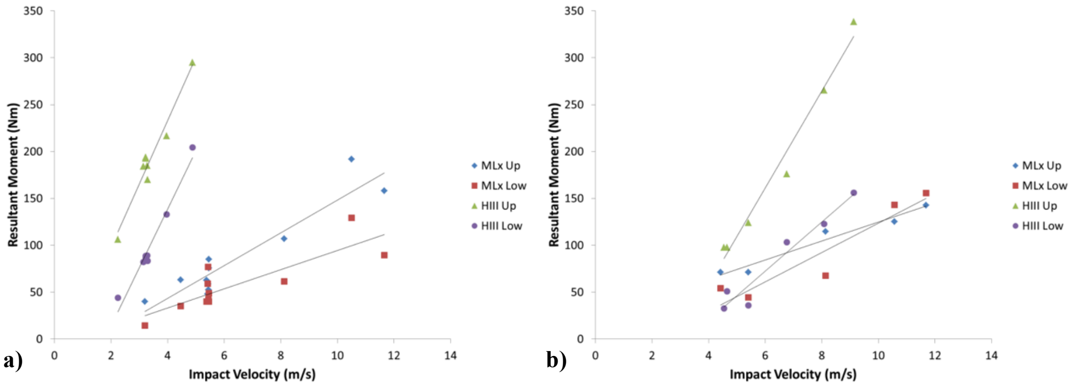

Figure 7. Peak resultant bending moments for Hybrid III (HIII) and MIL-Lx (MLx) ATD lower legs; a) unpadded condition, and; b) padded (with EA mat) condition.

4. DISCUSSION

This study subjected the standard Hybrid III ATD lower leg and the new MIL-Lx lower leg to impacts at high velocities (up to 12 m/s) representative of floor motion during an AV blast event. As the new NATO standard allows for either surrogate to be used for blast testing, each was evaluated against its respective injury threshold. Testing against energy attenuating floor mats allowed the legs to be evaluated at higher speeds than previously done and also allowed for the investigation of the effect of leg choice on the evaluation of protective capabilities of floor mats.

This is the first known study to examine both surrogates over this high range of impact speeds. A previous study [10] evaluated the response of the two surrogates, and for similar impact speeds achieved somewhat lower forces than found in the present study, but the trends between surrogates and between measurement locations are consistent. This difference in axial force between the two studies can be attributed to differences in experimental setup, where the previous study applied lower energy impacts, aligned the HIII tibia to be horizontal (rather than aligning the knee and ankle joints, as was done in the present study) and constrained the post-impact motion of both legs to the axial direction. A comparison between the two surrogates was also conducted using a Lower Leg Impactor [8], but due to the limitations of the Hybrid III load cells this testing could only be performed up to a maximum impact velocity of 3.4 m/s, even though the authors noted that injurious levels begin above 7 m/s. The forces recorded in the previous study were higher than those measured in the present study, also likely the result of differences in test setup and impact durations. Both legs were noted to be highly repeatable, with standard deviations of less than 8% of the peak force, but the pre- and post-test responses were not evaluated. The MIL-Lx was tested over a wide range of impact speeds (5.0 – 12.1 m/s) during its development, with the measured peak axial forces and bending moments agreeing well with those from the present study [4]. The authors, however, did not conduct similar tests on the Hybrid III surrogate.

For the unpadded condition in the current study, the Hybrid III and MIL-Lx legs exceeded their respective injury thresholds at different impact speeds (2.8 m/s and 6.0 m/s, respectively). This suggests that they are not equivalent test tools and methods for evaluating injury risk to the lower legs, as is suggested by the latest release of the NATO AEP-55 standard (14). However, when an EA mat was included, the differences in measured forces were less (4.4 m/s vs. 5.5 m/s for the Hybrid III and MIL-Lx legs), demonstrating the greater effect that EA products have on the response of the stiffer Hybrid III leg. As the EA mat had a greater effect on the Hybrid III surrogate than the MIL-Lx, evaluations of these protective products will depend highly on the choice of ATD used. As the MIL-Lx has a compliant element in place, the additional compliance of an EA product has less of an effect on the overall force response. As the MIL-Lx is considered to be representative of the natural leg [4,10], evaluations of EA mats conducted using the Hybrid III may overestimate the capabilities of these products. Furthermore, during its development the compliant element of the MIL-Lx was tuned to the unpadded condition. The added complexity of having two compliant elements in series (EA product and tibia) may result in a highly variable response under impact conditions not considered during the surrogate's development.

While not every vehicle will be equipped with EA mats, the added compliance could parallel that provided by boots, which have been noted to reduce axial forces in the tibia by up to 65% [10,5]. As the EA mat was found to have a lesser protective effect when tested using the MIL-Lx lower leg, it may be hypothesized that boots may similarly have less effect on the response of the MIL-Lx leg.

The current study highlighted several potential concerns with the MIL-Lx. While the axial force was highly linear and consistent, the resultant moments (particularly for the unpadded condition) had large variations. This has implications for the application of injury criteria such as the Tibia Index or Revised Tibia Index, which consider the contribution of bending moment towards injury risk [6,3]. Furthermore, when evaluating the repeatability and accumulated wear over the course of the test series, the post-testing forces were on average 3-4% lower than the pre-test forces. While this may not seem to be a large amount, this drop was observed after only 16 impacts of modest severity. Should repeated blast tests be conducted on this surrogate, there could be a more pronounced reduction in force, possibly due to damage of the heel pad or of the compliant tibia element.

5. CONCLUSIONS

The responses of the Hybrid III and MIL-Lx legs to high-speed impacts resulted in different evaluations of risk when compared to their respective injury criteria, and therefore these surrogates are not equivalent test devices. For a commercial Energy Attenuating floor mat, the forces in the Hybrid III leg were less than 34% of the unpadded condition at all speeds, but were greater than 67% of the forces in the unpadded MIL-Lx condition. This dramatic difference in response indicates that the selection of ATD leg for testing of EA mats will impact the evaluation of these systems and the assessment of their capabilities.

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