A Comparison of MiL-Lx and Hybrid-III Responses in Seated and Standing Postures with Blast Mats in Simulated Under-Vehicle Explosions.

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Abstract Blast mats that can be retrofitted to the floor of military vehicles are considered to reduce the risk of injury from under-vehicle explosions. Anthropometric test devices (ATDs) are validated for use only in the seated position. The aim of this study was to use a traumatic injury simulator fitted with 3 different blast mats in order to assess the ability of 2 ATD designs to evaluate the protective capacity of the mats in 2 occupant postures under 2 severities.
Tests were performed for each combination of mat design, ATD, severity and posture using an anti-vehicle under-belly injury simulator. The differences between mitigation systems were larger under the H-III compared to the MiL-Lx. There was little difference in how the 2 ATDs and how posture ranked the mitigation systems. Results from this study suggest that conclusions obtained by testing in the seated position can be extrapolated to the standing. However, the different percentage reductions observed in the 2 ATDs suggests different levels of protection. It is therefore unclear which ATD should be used to assess such mitigation systems. A correlation between cadavers and ATDs on the protection offered by blast mats is required in order to elucidate this issue.

Keywords Biomechanics, Blast injury, Blast mats, Hybrid-III, MIL-Lx

I. INTRODUCTION

Explosions under vehicles cause high rate axial loading to occupants' lower limbs, often resulting in debilitating injuries. Data from Afghanistan concerning casualties from under-vehicle explosions show that 91.5% of injuries are to the lower extremity [1], with the hind foot being a particularly susceptible zone of injury, resulting in particularly poor outcomes [2].

Quenneville and Dunning [3] conducted experiments using a Hybrid-III tibia to assess 5 blast mat designs. They utilised a mass of 6.8 kg travelling horizontally at velocities between 2.2 and 7 m/s to impact the sole of a Hybrid-III lower limb, which was disarticulated at the knee and fixed to a proximal bracket on a linear rail and bearing system. The mass of the proximal bracket is not reported and therefore it is not known if this represents realistically the mass of the rest of the body.

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The mass of the impactor was 6.8 kg. This is significantly lower than that used by other traumatic injury simulators that range between 24 kg and 42 kg [5-8]; however, the impulses measured by the load cell in the Hybrid-III are similar (~8 kN in 1 ms for an impact at 4.7 m/s with no combat boot). The blast mats were positioned below the sole of the Hybrid-III foot before testing. All blast mat designs reduced the force in the tibia; this reduction ranged from 35 – 77%. However, the effect of not connecting the lower limb to a mass which represents the rest of the body mass and using a low mass impactor on the response of the Hybrid-III is unknown.

Gangani and Vidye [9] developed a cost effective footpad. They performed physical blast tests with and without a blast mat. Unfortunately the methods used in the blast test with the floor mat differed from that of the test without the floor mat. The test without the floor mat was performed at the hull-level using a Hybrid-III, an axial tibia peak force of 13 kN was measured during this test. The test with a floor mat was performed in a vehicle level blast test with double the blast intensity resulting in a maximum floor pan velocity of 12.8 m/s in comparison to 9.0 m/s in the hull-level blast test. In the higher intensity test with a floor mat, the axial load measured on the Hybrid-III tibia was 8.0 kN in comparison to 13 kN in the lower intensity blast test without a floor mat. While the results of these tests demonstrate the potential effectiveness of floor mats the differences in methodologies between the experiments with and without the floor mat does not allow a percentage reduction in peak force to be calculated.

Masouros et al. [8] conducted a series of cadaveric tests using a traumatic injury simulator. They varied the posture of the cadavers from seated to braced to standing. They found that the injuries sustained in the standing position were significantly more severe than those in the seated position.

Instrumented human surrogates (anthropometric test devices, ATDs) are used to predict how a human would behave under load. The 2 most commonly used ATDs for the lower extremity are the Hybrid-III and the MiL-Lx, both of which are recommended by the North Atlantic Treaty Organisation (NATO) [10]. The MiL-Lx has been specifically developed for under-vehicle explosions, whereas the Hybrid-III was originally designed for the automotive industryBoth McKay [11] and Pandelani *et al*. [12] demonstrated that the response of the MiL-Lx is more biofidelic than the Hybrid-III in terms of impulse, and Newell *et al*. [6] demonstrated that the MiL-Lx was more biofidelic than the Hybrid-III in terms of behaviour of the mitigation technology itself (significantly more compression of the combat boot was seen under the Hybrid-III than the MiL-Lx or cadaver). Assessments of vehicles are made by measuring the axial force transmitted through the tibiae of the ATDs. The threshold axial force for the MiL-Lx is 2.6 kN measured at the upper tibial load cell and for the Hybrid-III is 5.4 kN measured at the lower tibial load cell. Both Hybrid-III and MiL-Lx lower extremities are validated for testing in the seated position only and have not previously been tested in a standing position [10].

The aim of this study was to compare the response of Hybrid-III and MiL-Lx using 3 different blast mat designs in both the seated and standing positions at a range of impact severities.

II. METHODS

All tests were performed using our anti-vehicle under belly injury simulator (AnUBIS) at room temperature (22 ± 1 °C). Operation of the rig is discussed extensively elsewhere [6,13]. Briefly, lower limb specimens rest on a 42 kg plate which is being driven upwards pneumatically; the driving pressure is controlled by shear pins of various materials and dimensions.

The tests were performed at 3 severity levels: low, medium and high using 12 mm nylon, 9.5 mm brass and 12.7 mm brass shear pins, respectively. The medium level of severity in the seated and low level of severity in the standing experiments were chosen based on preliminary tests whereby the peak force measured on the appropriate tibia load cell of the ATDs was marginally above the threshold values set by NATO [10]. The high severity is the same as that used in previous cadaveric and ATD studies using similar techniques [6,8]. Table I shows a matrix of the tests conducted on both the Hybrid-III and MiL-Lx.

TABLE I

MATRIX OF THE TESTS CONDUCTED. THESE TESTS WERE REPEATED ON BOTH THE MIL-LX AND THE HYBRID-III.

	Seated			Standing		
Protection	Low severity	Medium severity	High severity	Low severity	Medium severity	High severity
No Protection	-	2	2	2	2	-
Blast mat A	-	2	2	2	2	-
Blast mat B	-	2	2	2	2	-
Blast mat C	-	1	1	1	1	-

Plate acceleration and pressure at plate release were recorded by an accelerometer (model 352C04, PCB Piezotronics Inc., NY, USA) that was secured to the plate and a pressure transducer (Pi602, Applied Measurements, Berkshire, UK), respectively. The velocity of the plate was calculated by integrating the accelerometer signal. The signals were sampled at 25 kHz by a National Instruments PXIe system (Newbury, Berkshire, UK) and a custom written LabView code. An anti-aliasing filter was used on the accelerometer and pressure transducer as part of the PXIe data acquisition system. The Hybrid-III is instrumented with 4-axis load cells in the upper and lower sections of the tibial shaft and the MiL-Lx is instrumented with a 5-axis load cell in the upper tibia. The ATDs were sampled at 25 kHz using a Saturn AMO System (AMOtronics UG, Aachen, Germany).

The mounting for the standing and seated tests can be seen in Figure 1. In the standing cadaveric tests described by Masouros et al. [8] the extensor mechanism of the knee joint was simulated by applying a tension through a rod fitted in a hole drilled through the patella. The ATDs do not have a patella, so this force was applied by attaching eye bolts to the knee clevis of the ATDs thus allowing tension to be applied through cables. The surrogate hip joints in both the standing and seated position allow weights to be positioned on a cross-bar to simulate a typical half body weight. Without the simulated extensor mechanism the knee joint buckles under body weight in the standing position.

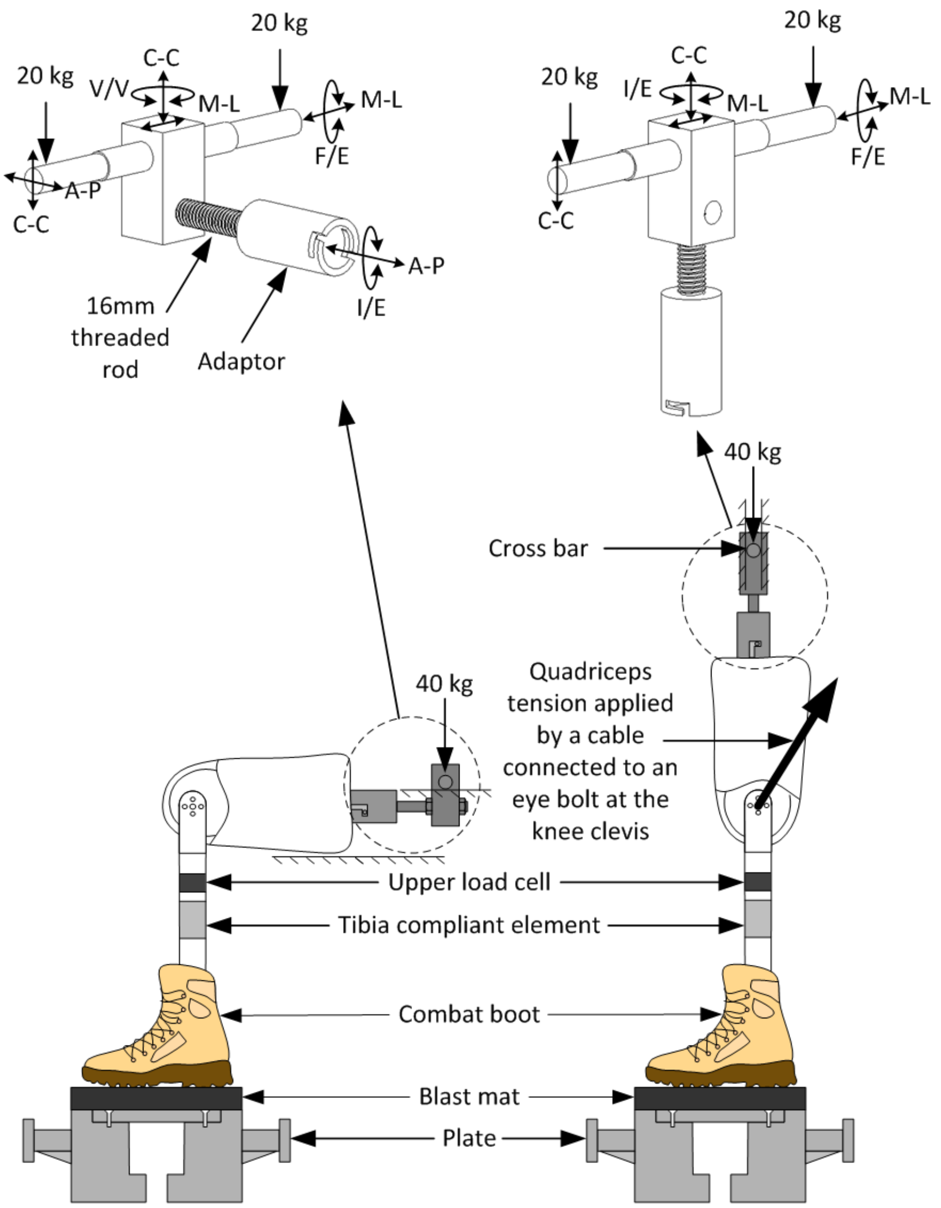

Fig. 1. Configuration and mounting for the seated and standing MiL-Lx leg. The same setup is used for the Hybrid-III tests. F/E: Flexion/Extension, I/E: Internal/External rotation, V/V: Varus/Valgus (or ab/adduction); M-L: MedioLateral translation, A-P: AnteroPosterior translation, C-C: CranioCaudal translation.

Size 10 Meindl Desert Fox Combat boots (Lucas Meindl GmbH and Co, Kirchanschoring, Germany) were fitted to each of the ATDs and replaced after 5 tests. In previous tests we have conducted with the Hybrid-III, use of the same combat boot for over 10 tests produced standard deviations within 5%, therefore informing our decision to replace the combat boot after 5 tests, rather than every 1. A new blast mat was used for each test; the mat was placed under the foot of the respective ATD (Figure 1). Dimensions and mass of each blast-mat sample were measured prior to testing.

III. RESULTS

Table II shows the mean values for the pressure at release and maximum speed of the plate. No significant differences were seen in maximum velocity and pressure at release at each severity between tests ($p < 0.05$, Student's t-test).

TABLE II

MEAN VALUES ± 1 SD FOR PRESSURE AT RELEASE AND MAXIMUM SPEED OF THE PLATE

		Standing		Seated	
	ATD	Low severity	Medium severity	Medium severity	High severity
Pressure at release (bar)	H-III	2.92 ± 0.32	5.81 ± 0.18	5.86 ± 0.15	9.63 ± 0.15
	MiL-Lx	2.76 ± 0.11	5.84 ± 0.13	5.70 ± 0.31	9.91 ± 0.48
Maxium speed (m/s)	H-III	2.78 ± 0.15	5.89 ± 0.30	6.49 ± 0.24	8.85 ± 0.16
	MiL-Lx	2.99 ± 0.08	6.23 ± 0.18	6.51 ± 0.15	9.11 ± 0.34

Mass, volume and specific mass (as a measure of effective density) of the blast mats are shown in Table III.

TABLE III

PHYSICAL PROPERTIES OF THE BLAST MATS

	Blast mat A	Blast mat B	Blast mat C
Mass (kg)	0.50	1.33	0.73
Volume (×10^6 mm^3)	1.82	3.03	1.23
Thickness (mm)	30	55	28
Specific mass (g/cc)	0.29	0.44	0.60

Typical tibial axial force traces from the seated and standing tests are shown in Figures 2 and 3, respectively. Figure 4 shows the peak axial forces in MiL-Lx and Hybrid-III for all tests. The forces seen on the Hybrid-III are consistently higher than those seen in the MiL-Lx for the same severity, posture and mat design. All mats reduce the maximum force in the Hybrid-III at all severities and in all postures, except for Blast mat C in the low severity standing test. In the seated, high severity tests the Hybrid-III ranks the mats in the following order (from worst to best): 1) Blast mat C, 2) Blast mat A and 3) Blast mat B. This ranking is the same in the low severity tests. The MiL-Lx ranks the mats in the same order as the Hybrid-III, albeit the differences from the force in the unprotected case are substantially less than those seen in the Hybrid-III. In the medium severity MiL-Lx tests no mat reduces the axial force below the 2.6 kN threshold, whereas in the respective Hybrid-III tests all mats reduce the force below the 5.4 kN threshold.

In the standing medium severity tests with the Hybrid-III, the mats rank as follows (from worst to best): 1) Blast Mat C, 2) Blast mat A and 3) Blast mat B; this is the same as the seated tests. This ranking holds for the low severity tests as well. The MiL-Lx ranks the blast mats in the same order as the Hybrid-III in the medium severity tests, except that blast mat A performs similarly to blast mat C. In the low severity MiL-Lx tests, all axial force traces were similar; the peak force was 4.0 ± 0.7 kN.

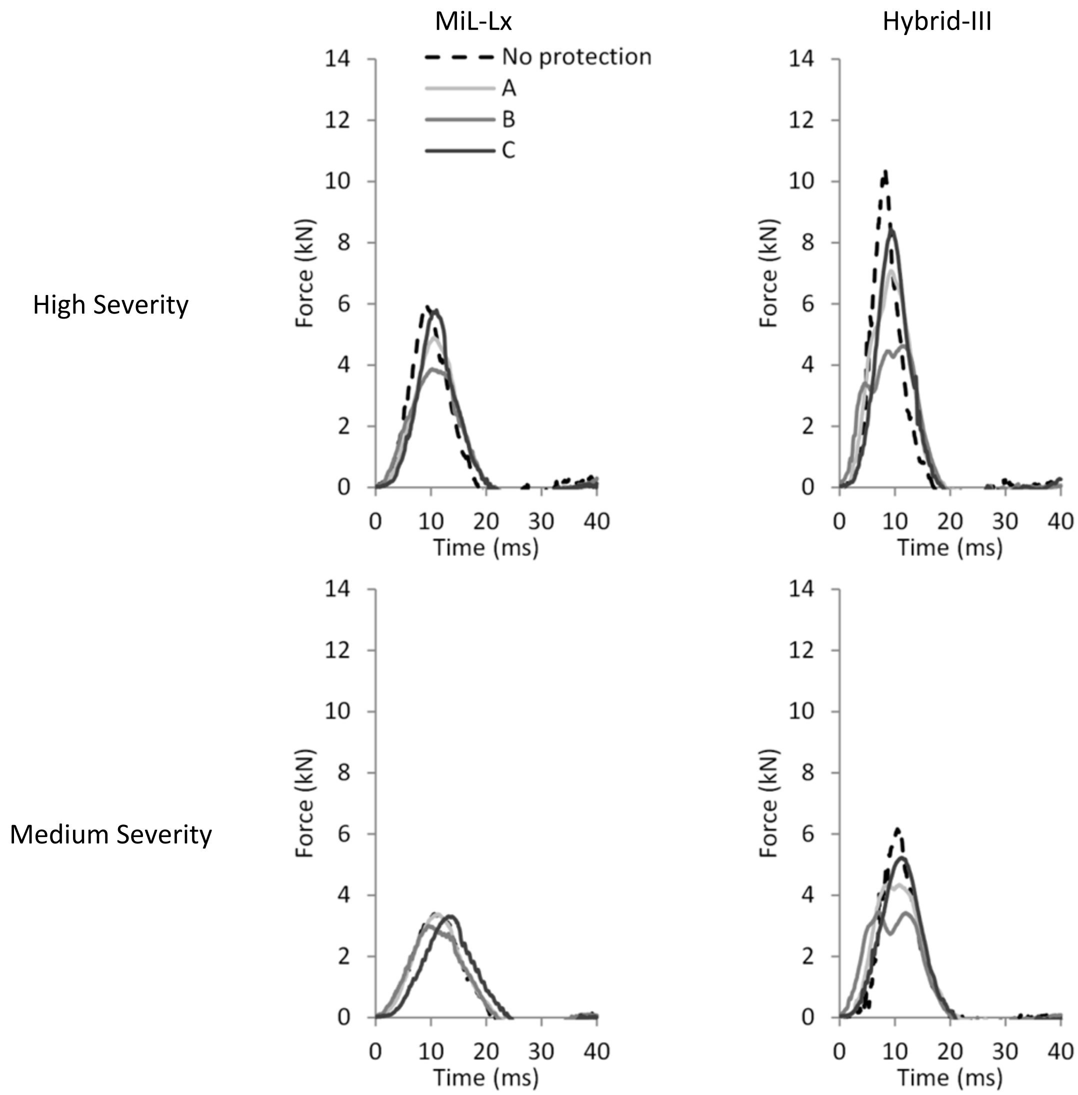

Fig. 2. Typical force-time curves from the seated tests.

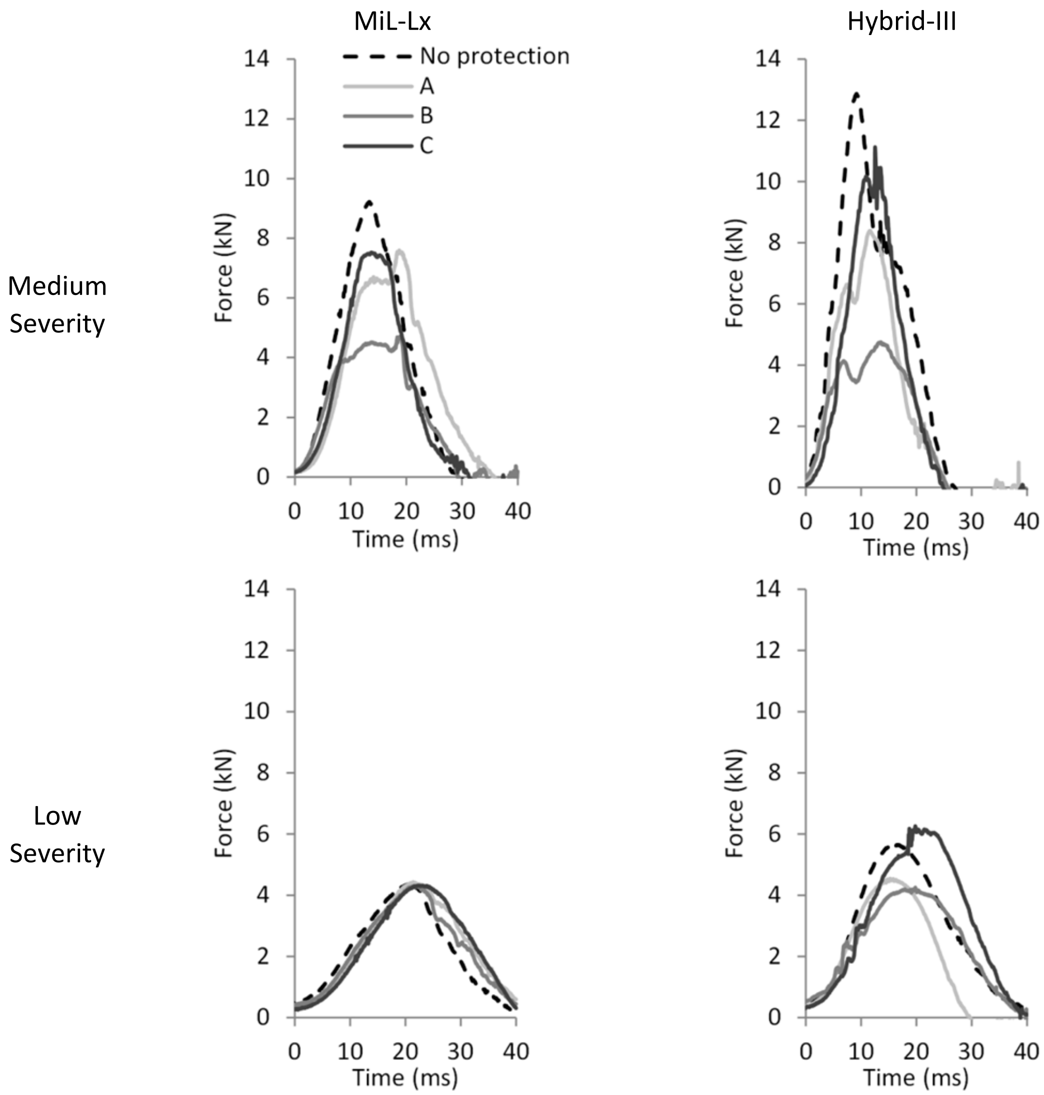

Fig. 3. Typical force-time curves from the standing tests.

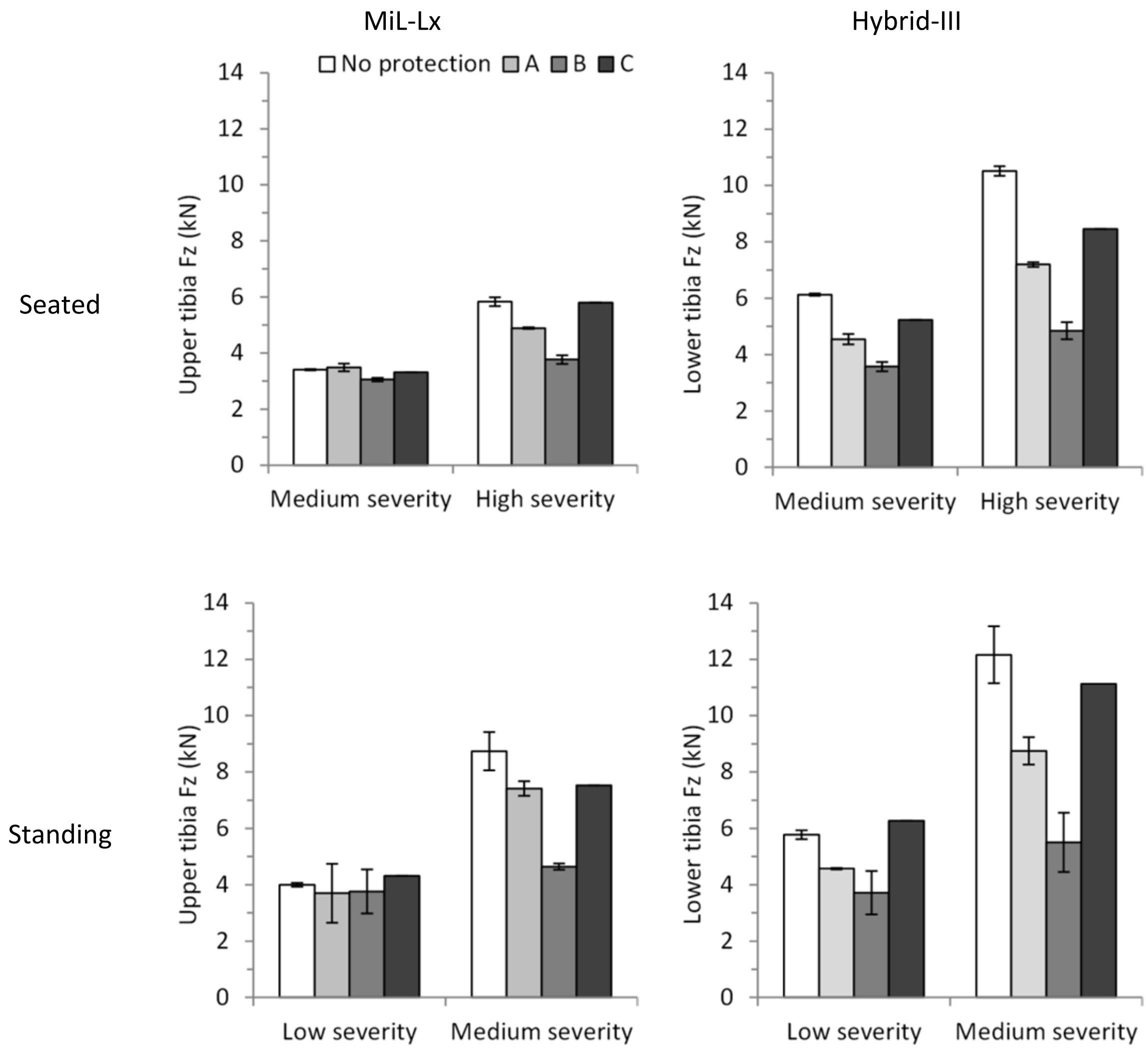

Fig. 4. Peak axial force in the upper tibia of the MiL-Lx and the lower tibia of the Hybrid-III for the seated and standing tests. Error bars represent ±1 SD; they are present in tests with at least 2 repeats.

IV. DISCUSSION and CONCLUSIONS

A series of trials was performed using AnUBIS in order to compare the sensitivity to prediction of lower limb injury of 2 types of ATD in 2 postures with 3 types of mitigation. The ATDs rank the mats similarly irrespective of posture in the higher severity tests per posture, whereby the axial force response of the unprotected ATD was substantially greater than the NATO-standard threshold value. In the less severe tests for each posture, whereby the axial force response of the unprotected ATD was only slightly greater than the NATO-standard threshold value, the MiL-Lx showed very similar behaviours between mats, with minimal - if any - reduction in axial force; conversely, the H-III showed that all mats were reducing the injury risk below the accepted threshold.

When comparing posture, the peak force in the medium severity tests is consistently higher in the standing position than the seated position under both ATDs with all blast mats and with no protection at all. This is consistent with the findings of Masouros et al. [8] who showed that the injuries seen in cadavers in the standing position are more severe than those seen in the seated position. The cadaveric tests were performed at the high severity for both seated and standing. High severity tests in a standing position were not conducted in this study, as the load cells would have been overmatched.

The axial force recorded in the MiL-Lx was always lower than that recorded in the H-III for the same severity, posture and mitigation system; this is likely to be due to (a) the higher compliance of the MiL-Lx in comparison to the Hybird-III, and (b) the MIL-Lx load being measured at the upper tibia, compared to the H-III load being measured at the lower tibia. It should be noted that the upper tibia load of the H-III is consistently lower than that of the lower tibia in the seated posture, but similar in the standing posture.

These results suggest that blast mat B out performs A and C; however, it must be noted that the thickness of blast mat B was greater than that of the other 2 mats. It is likely that the thickness of the blast mat – and therefore effective stand-off of the foot – is an influential variable in achieving higher levels of protection.

Previous research has shown that the MiL-Lx is more biofidelic than the Hybrid-III in simulating the response of the lower extremity in under-vehicle blast. Our tests show that a potential decision on vehicle operational fitness and effectiveness of mitigation would depend on the ATD used. Further experimentation with cadaveric specimens and a range of mitigation systems is required to determine whether and which ATD is capable of assessing the effectiveness of these types of systems in under-vehicle blast.

The concluding remarks from this study could be summarised as follows:

1. The axial loads recorded in the MiL-Lx are lower than those recorded in the H-III for the same severity and posture.
2. The axial loads recorded in the standing posture are higher than those recorded in the seated for the same severity and ATD.
3. The differences between mitigation systems are larger under the H-III compared to the MiL-Lx.
4. There is little difference in how the 2 ATDs rank the mitigation systems.
5. There is little difference in how posture ranks the mitigation systems.

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