VALIDATION OF LOWER LIMB SURROGATES AS INJURY ASSESSMENT TOOLS IN FLOOR IMPACTS DUE TO ANTI-VEHICULAR LAND MINES

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ABSTRACT

The aim of this study is to assess the ability of lower limb surrogates to predict injury due to floor/footplate impact in military vehicles during anti-vehicular (AV) landmine explosions. Two biomechanical surrogates; 50th percentile Hybrid III foot/ankle and THOR-Lx, were evaluated against previously established corridors. Two loading conditions were simulated to represent those conditions created in the field provided by the NATO RTO HFM 090 TG25 working group. Results show a better correlation to the corridors with the THOR-Lx for the lower impact condition. However, future work is needed including the evaluation of frangible surrogates.

Keywords: explosion, biofidelity, PMHS, cadavers, dummies, legs, validation

ANTI-VEHICULAR (AV) LANDMINES have been associated with a major loss of vehicles as well as occupant injury during times of conflict. Losses of military vehicles due to landmines have increased from 22% in World War II to 60% in the most recent conflict in Somalia (Bird, 2001). In addition to causing vehicle damage, AV landmines have the ability to cause harm and serious injuries to the occupants. During the Rhodesian war in the 1970s, 2,405 landmines were detonated by military vehicles, causing 632 deaths and 4,410 injuries (Bird, 2001). These injuries are due to fragmentation, blast overpressure, vehicle shock acceleration and deformation, loss of vehicle control and gross vehicle movement.

BACKGROUND

Wang et al. (2001) noted that, in a medium sized armored vehicle, the average floor acceleration and velocity typically exceed 100 g and 12 m/s, respectively, during an AV landmine blast. They proposed ways to minimize the impact of the blast on the occupant by using a vehicle false-floor built from two energy absorbing materials. A honeycomb material was tested using specially designed Australian Defense Science and Technology Organization's (DTSO) frangible synthetic legs (FSL) in an explosion test. It was found that, using the same explosive charge (200g of PE4) the FSL fractured with no false-floor, and remained intact when the false-floor was used. This charge produced an average acceleration of 1,000 g with duration of 2ms (Wang, 2001).

Surrogates, such as the Hybrid III dummy and FSL, were also used in studies by Bird (2001) where four different military vehicles were tested to establish the mechanism of injury during mine blasts. The authors determined the principal cause of lower leg injuries was due to floorboard intrusion. Recommendations were made based on the findings and included the use of special purpose vehicles in areas with known landmines, incorporating mine protection into the design of the vehicles, and adapting previously manufactured vehicles both in the factory and in the field.

Radonic et al. (2004) reported on injuries from AV landmines during the war in Croatia during a five year period. Of the 42 vehicle related occupant injuries reported 12 resulted in a fatality. Three of the severe injuries resulted in traumatic amputation on the upper leg with one additional patient having sustained traumatic amputation of both upper legs. Traumatic amputation of the lower leg was noted in two cases with calcaneous fractures of the opposite leg. An additional six calcaneus fractures

were reported with two reporting fractured tibias and one reporting a femur fracture. Although not life threatening the effects of these injuries can be long term (Radonic, 2004).

The incident of fractures to the lower extremity in vehicle crewmen has also been reported during the war in Afghanistan. When investigating injuries related to the war Nechaev et al. (1995) reported that approximately 64% of fractures occurring during AV landmine explosions were to the lower extremity. Twenty percent of the fractures were to the upper extremity, while the remaining 16% were to the pelvic and spine (Nachaev et al., 1995).

To further delineate injuries in a controlled setting, testing was conducted using the Test Rig for Occupant Safety Systems (TROSS™) developed by IABG (Lichtenau, Germany) in cooperation with WTD 91 (Meppen, Germany). This test fixture consists of a membrane bottom plate and a footplate on top of it. It is closed off by a box to which a seat is attached. The structure is not coupled to the floor, so seat motion does not affect lower limb loading. The seat is made up of a simple steel chair with a straight back and a two-point seat belt is used to restrain the motion of the dummy. The seat is adjustable to make sure that the position of the femur and the feet are consistent. The loading of the footplate is generated by small explosive charges under the bottom plate.

The TROSS™ was developed to use scaled detonations and provide the same input to an occupant as during a full-scale test. The loading produced by small charges detonated under the TROSS™ is comparable to a real mine (2 to 10 kg TNT) detonation under a light military vehicle. The TROSS™ offers the possibility to provide well-defined and reproducible loads by the detonation of small explosive charges under an elastic deformable membrane bottom plate. Figure 1 shows the exterior and interior views of the TROSS™. The test rig is closed by a box, which is de-coupled from the membrane plate and thus, isolated from the shock of the detonation.

Figure 1: Test Rig for Occupant Safety Systems (TROSS™) developed by IABG (Lichtenau, Germany) in cooperation with WTD 91 (Meppen, Germany).

Testing was conducted with the TROSS™ using a full Hybrid III dummy with both the Hybrid III lower limb and the THOR-Lx attached. The surrogate was positioned such that the leg was centered on the membrane plate. Several tests were performed with increasing severity (Conditions 1, 2, 3) with and without boots. The key parameters explored included tibia loading in the z-direction and the total plate displacement. The results for the Hybrid III lower limb can be seen in Table 1. The presence of the boots decreased the overall loading by approximately 30-40% given similar plate displacements. Condition 3 was only tested with the boot in place due to the limitations of the load cells within the surrogate.

Hybrid III	**Plate displacement (mm)**	**Peak plate velocity (m/s)**	**Tibia Force - Z (N)**
Condition 1 no boot	12.3	2.0	5970
Condition 1 boot	12.6	2.0	3709
Condition 2 no boot	21.8	3.4	10740
Condition 2 boot	20.5	3.4	7000
Condition 3 boot	27.1	4.5	9984

Table 1: Results from testing conducted using TROSS system and Hybrid III surrogate.

In response to the NATO/Research and Technology Organization/Human Factors Panel ET 007 identification of the lack of data surrounding AV landmine injury assessment, the NATO Research and Technology Organization/ Human Factors Panel 090 Task Group 25 was formed. This working group identified a need to determine the most appropriate surrogate and injury criterion for AV landmine exposure. The ability to determine the most appropriate surrogate is an important step in developing a methodology to assess injuries to occupants during AV mine blasts. It is critical that the selected surrogate, with respect to the PMHS response, enables the determination of injury criteria, which will most accurately predict fracture and other injuries.

In previous efforts to evaluate the effects of AV landmines on the human occupant, different types of surrogates have been used. These included both biomechanical as well as frangible surrogates (Bird, 2001, Wang, 2001, Manseau, 2005). For the purposes of this report, biomechanical surrogates are defined as multi-use testing devices that give repeatable mechanical responses and can measure physical parameters, such as load, that can ultimately be linked to injury predictions. Frangible surrogates are single-use testing structures that are designed to fracture in a manner similar to how a human body would injure. Both offer the ability to predict injuries without the need to extensively test post-mortem human specimens (PMHS). Since the use of human volunteers is not possible, PMHS has been routinely used as a conservative model for the initial validation of the surrogates prior to use in testing. The current effort is focused on the evaluation of biomechanical surrogates.

BIOMECHANICAL HUMAN SURROGATES: Two different biomechanical surrogates were explored. The Hybrid III dummy is an automotive crash test dummy that is commonly in use in the automotive industry. The lower limb consists of a pin joint at the knee and a ball joint at the ankle. It contains upper and lower tibia load cells capable of measuring moments and forces. The shaft of the tibia in the Hybrid III is translated anteriorly at its proximal end and slightly posteriorly just above the ankle (Hybrid III, 1994).

The Test Device for Human Occupant Restraint (THOR) is the latest impact dummy developed by National Highway Traffic Safety Administration (NHTSA) (Owen, 2001). Their aim when developing the new dummy was to offer increased biofidelity and measurement capability compared to the Hybrid III. The improvements made on THOR that are relevant to this study include: a compliant tibia element which modulates the response to the axial impact more realistically, three independent axes of rotation for the ankle, where flexion and extension properties are based on human ankle tests, the existence of an Achilles tendon simulated by a tensioned wire, which contributes to more realistic axial forces, and additional instrumentation including mid tibia and mid foot accelerometers, and an ankle angle potentiomenter. The THOR-Lx leg uses a straight-line shaft as opposed to the Hybrid III.

Although these biomechanical surrogates have been tested extensively in automotive impacts, their utilization for evaluation of AV landmine loading needs to be critically examined due to the different loading conditions. The application of these surrogates for evaluation of landmine protection requires additional validation related to the specific mine induced loads and injuries. AV landmine loading produces input forces to the lower limb that are mostly vertical with a much higher level (up to 10 times) and shorter duration (<10 ms vs > 100 ms) than seen with automotive impacts (Horst et al., 2005). It has been reported that in a medium sized armored vehicle, the average floor acceleration and velocity typically exceed 100 g and 12 m/s during an AV landmine blast (Wang et al., 2001). This is in comparison to automotive impacts which have been simulated at 2 to 6 m/s with acceleration levels of approximately 40 g (Owen, 2001). Given the vertical loading conditions, injuries are most commonly seen to the calcaneous and lower portion of the tibia and fibula (Radonic 2004). Establishing the biofidelity of the surrogates for use in evaluating AV landmine loading is essential.

HUMAN RESPONSE CORRIDORS: The use of PMHS is critical when establishing how the body responds to a given impact. As part of the initial effort, testing was conducted on twelve PMHS (Barbir, 2005). The lower limbs of all specimens were harvested at the femur approximately 7 inches from the knee. The specimen was potted into a device designed to interface with the Hybrid III surrogate. Dean-El et al. (2003) was used as a guide for implanting a tibial load cell (Denton, Inc, model 3786J). A gap osteotomy was performed along the diaphysis of the tibia in an effort to implant the load cell at approximately midshaft. During the preparation a positioning rig held the remaining bone aligned. The load cell was held in place using stainless steel potting cups, as described by Dean-El et al. (2003). After the load cell was in place, the skin flaps were sutured together and the leg was wrapped with a flexible bandage (Barbir, 2005).

For both the previous effort (Barbir, 2005) and the current effort, the results from the TROSS™ tests were used to recreate the loading event in the laboratory setting. A linear impactor device was used to recreate the five distinct impact conditions in Table 1. Testing was focused on condition 2 and condition 3, since these conditions were more representative of loading conditions causing injuries in the field.

All specimens were attached to the Hybrid III surrogate after the tibia load cell was implanted, with the foot reported as being held in natural position prior to impact (Barbir, 2005). A total of at least five tests per impact condition 2 and 3 were reported. Only one test per specimen was conducted. Corridors were developed by averaging the normalized force-time curves and taking one standard deviation on either side of the average. Normalization was performed following an equal stress - equal velocity normalization method (Cavanaugh, 1986), based on the assumption of equal mass density and equal moduli of elasticity in all test subjects. The mass of the leg was used to determine the normalization factor. For condition 2, the peak tibia forces within the corridor were reported to be between 2882 N and 4329 N. The peak duration ranged from 8 to 15 ms. For condition 3, the corridor established a peak tibia axial force in the range between 3681 N and 5834 N. The duration of the event ranged between 8 and 16 ms (Barbir, 2005).

The current effort explores the ability of two biomechanical surrogates to predict injuries from AV land mine loading. Previously established corridors and output from live fire testing was used to evaluate the biofidelity of both the Hybrid III and THOR-Lx lower extremity surrogates. With the identification of such a suitable surrogate, it is possible to more accurately test the ability of various countermeasures to reduce injury to occupants in vehicles encountering AV land mines.

METHODOLOGY

As with the corridor development, a linear impactor was used to replicate the input conditions provided from the TROSS™. The dummy was positioned supine on a table. The lower limb was raised at a 90º angle relative to the torso, and the leg was re-positioned horizontal to the ground (90º to the upper leg). The bottom of the foot was aligned approximately parallel to the impactor plate. The right lower limb was bent at the knee and rested on its foot (Figure 2). The table was raised such that the center of the heel of the foot of the impacted lower limb was aligned with the center of the plate. This meant that the impact occurred straight through the shaft of the leg, which insured acceleration and force curves with a single peak. It was found that if the foot is impacted on a more distal point, dorsiflexion of the foot create a second peak. The first peak occurred during the initial contact, and the second during the contact with the heel.

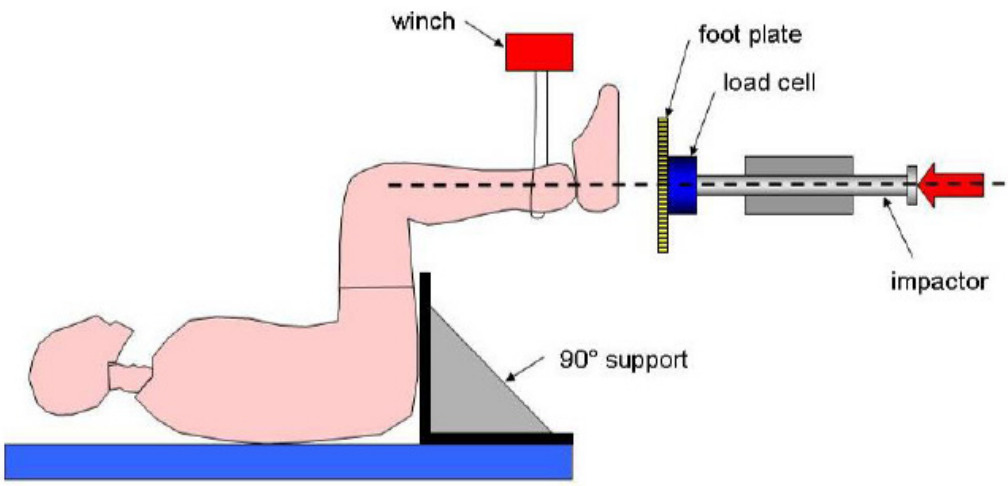

Figure 2: Positioning of surrogate for impact.
(Barbir, 2005)

When developing the testing protocol, there were two key parameters that needed to be matched to the explosives test in order to insure the lower limb was being subjected to a similar impact. First the footplate displacement and secondly the tibia force in the z-direction (See Table 1). A distance laser

transducer (Micro-Epsilon Corporation, model LD 1625-200) was used to measure footplate displacement. The leg was instrumented with a standard triaxial tibia force transducer at the lower tibia (Denton, Inc, model 1584). The mass, pressure, and free flight distance of the impactor, as well as the stiffness of the honeycomb material were tuned to match the conditions of the TROSS™ explosives tests.

For conditions 1 and 2, the measurements from the bare foot TROSS™ tests were used as baselines for recreating a similar impact with a linear impactor. The booted case for each of the two conditions was then conducted using the same settings. For condition 3, the anticipated forces for the bare foot case were above the limits of the load cells used, and therefore, the values from the booted case were matched.

For condition 1, the impactor was a stainless steel cylinder, load cell (Interface, model 1210-AJ-5000-84638), and 12 in^2 footplate with total mass of 37 kg. An 800 kPa piece of hexcel was used to decelerate the impactor. It was found that using this hardware, together with initial settings of pressure that produce an impactor velocity of 3.8 m/s, yielded results that best matched the TROSS data (Figure 3).

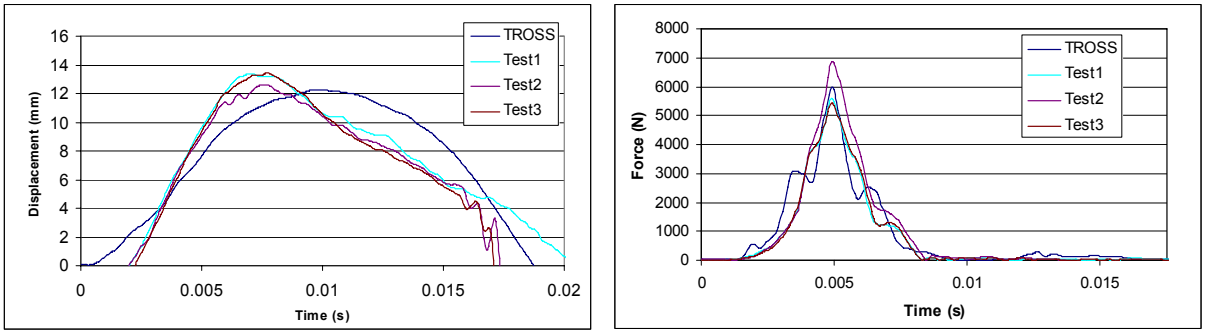

Figure 3: Comparison of linear impactor data with TROSS™ testing using Hybrid III lower limb for Condition 1.

For condition 2, a lighter, aluminum impactor with two weights inside was used. A different load cell (Denton, Inc, model 66501-5k) was used as well. However, the same footplate was used. The total mass of the system was for condition 2 was 24 kg. The footplate distance and the tibia force were both found to best match the TROSS™ data at an average impactor velocity of 4.7 m/s (Figure 4). The oscillations that occur during the displacement curves are due to the vibration of the plate during impact.

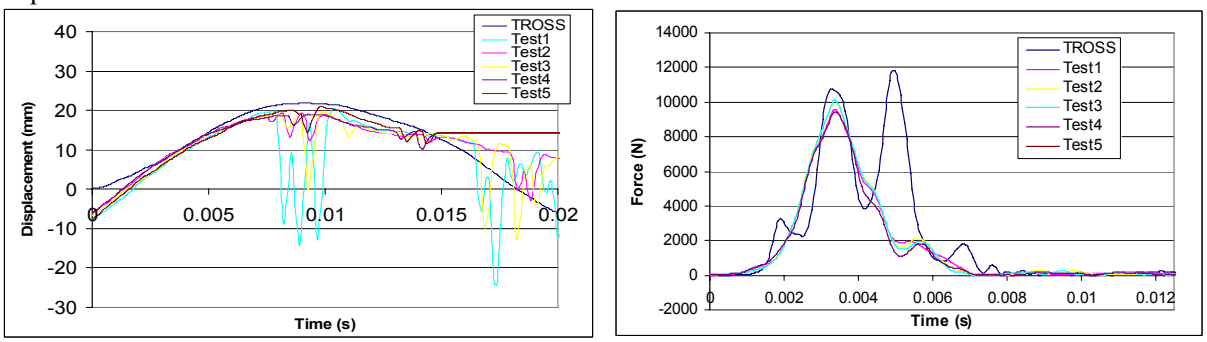

Figure 4: Comparison of linear impactor data with TROSS™ testing using Hybrid III lower limb for Condition 2.

For condition 3, only the booted condition was matched similar to the TROSS testing, as the forces at the tibia load cell for the foot impact were anticipated to be over the tibia load cell tolerance limit. The stainless steel impactor used for condition 1, the load cell (Denton, Inc, model 66501-5k), and footplate were found to yield the closest match given the mass of 37 kg and average impactor velocity of 8.3 m/s (Figure 5). Due to the severe vibrations experienced by the plate during impact, video analysis was conducted to produce the displacement curves. High-speed video was collected using a HG 100K Camera (Redlake, Inc) at 10,000 frames per second with a given resolution of 256 X 192 pixels.

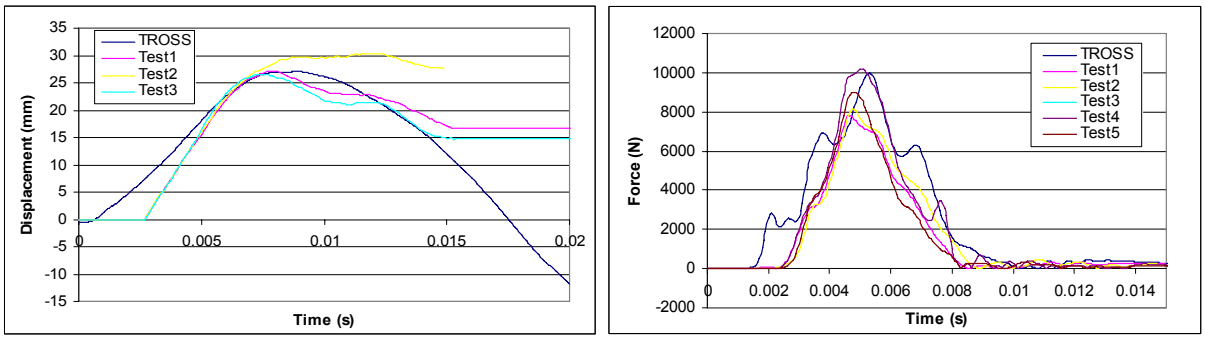

Figure 5: Comparison of linear impactor data with TROSS testing using Hybrid III lower limb for Condition 3.

After validation of the impact conditions, the standard Hybrid III lower limb and THOR-Lx v3.2 (model T1LXM000) surrogates were attached to the full body surrogate. A lower tibia load cell (Denton, Inc, model 1583) was placed in the Hybrid III leg. In an effort to obtain additional loading data, a Foot/Ankle assembly (Denton, Inc, model 6220) was used in place of the standard Hybrid III 50th percentile foot. The tibia shaft and instrumentation, as well as the dummy to which they were attached, remained the same. The foot/ankle assembly provided additional outputs to the existing lower tibia load cell force, namely the ankle and the toe forces. Data were collected using a TDAS Pro (DTS, Inc) at 20,000 Hz. Filtering of the data was completed as reported in table 2.

	Filter Class	Filter Frequency
Footplate Displacement	2nd order Butterworth	1000
Acceleration (Tibia, Plate, etc.)	CFC 600	1000
Force (Tibia, Plate, etc)	CFC 600	1000

Table 2: Filtering specifications for surrogate testing data.

RESULTS

Since corridors are only available for conditions 2 and 3 without boots, force-time results from all remaining tests conditions are not presented. However, summary results from these tests can be found in Tables 3 and 4.

	Tibia Force (N)	Toe Force (N)	Ankle Force (N)
Condition 1 no boot	6520	1162	8905
Condition 1 boot	3833	549	4439
Condition 2 no boot	10017	1440	13782
Condition 2 boot	6052	733	7576
Condition 3 boot	9897	1258	12165

Table 3: Results from Hybrid III testing with linear impactor.

	Lower Tibia Force (N)	Upper Tibia Force (N)
Condition 1 no boot	2972	2414
Condition 1 boot	2504	2303
Condition 2 no boot	3845	2910
Condition 2 boot	3194	2601
Condition 3 no boot	7316	*
Condition 3 boot	5309	3706

* Cannot be determined due to limits of mechanical structure, see discussion.

Table 4: Results of THOR with linear impactor.

For the Hybrid III leg, the average maximum lower tibia force under Condition 2 was 10017 N, which is 2.8 times the average maximum tibia force measured in PMHS tests. The force duration is approximately 6 ms, which is between two and three times smaller than that experienced by a cadaver tibia (Figure 6). Although loading at the toe region was not significant (1440 N), forces at the ankle region exceeded 13000 N. This was a 38% increase over the loading seen at the tibia.

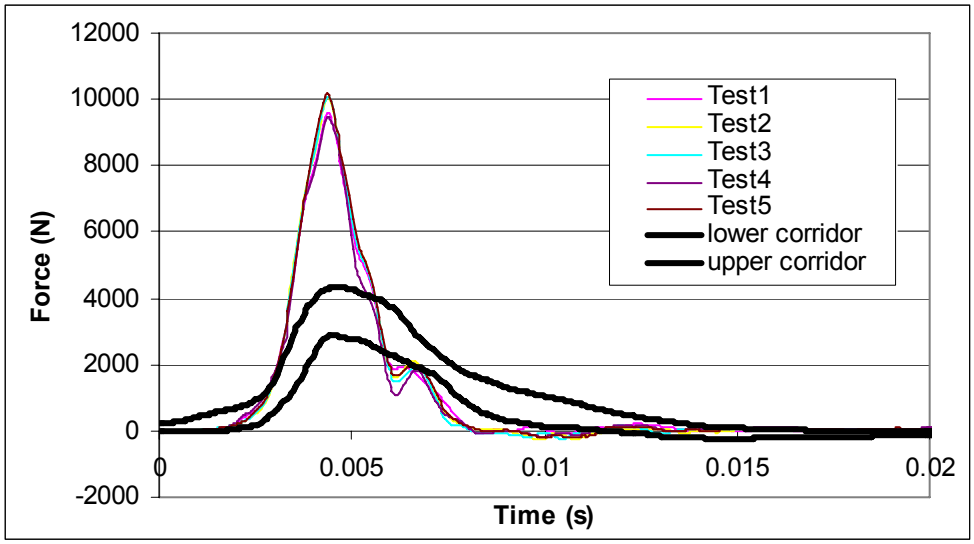

Figure 6: Force-time curves from Hybrid III – Condition 2.

Six tests were completed with the THOR Lx under Condition 2. The average lower tibia load was calculated at 3845 N, which fits within the bounds of the corridor constructed from normalized PMHS data as seen in Figure 7. The average force duration was approximately 12 ms, which also fits within the time range of the established corridor.

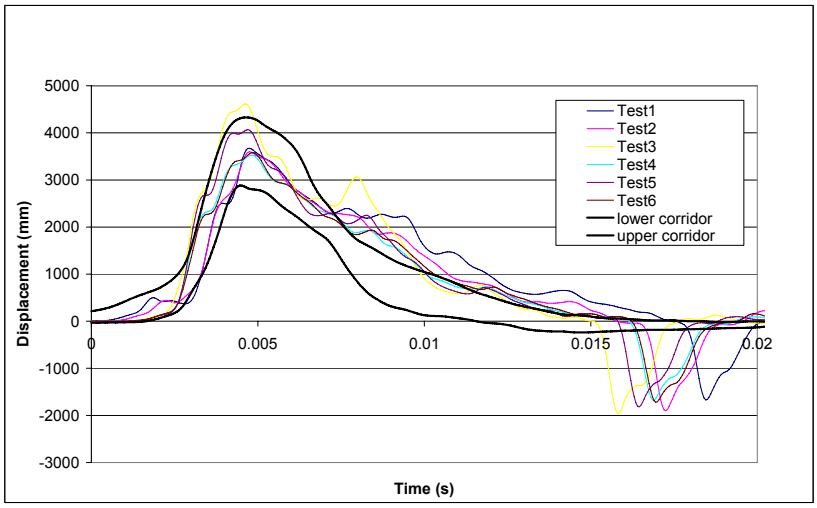

Figure 7: Force-time curves from THOR – Condition 2.

Testing was conducted using the Hybrid III lower limb with a protective boot in place to determine potential peak loads during Condition 3. The average force experienced by the Hybrid III lower tibia under Condition 3 with a boot was 8557 N, with the highest test reaching over 10000 N. Based on previous testing (Barbir, 2005), the tibia force measured with boots was approximately 50% less than that measured without boots. This would imply an expected Hybrid III tibia force on the non-booted case of Condition 3 in the range between 15000 and 20000 N. The tolerance limit of a standard Hybrid III lower tibia load cell is 15000 N. Therefore, testing was not conducted on the Hybrid III with Condition 3.

The THOR lower limb in Condition 3 yielded a force-time curve that was bimodal. The average absolute peak force was 8646 N with the average first peak being 7316 N. As illustrated by Figure 8, this is outside the range of the Condition 3 corridor established by PMHS tests. The force duration for the entire event for the PMHS testing without a boot is 10 ms, while the first peak lasts only about 3 ms.

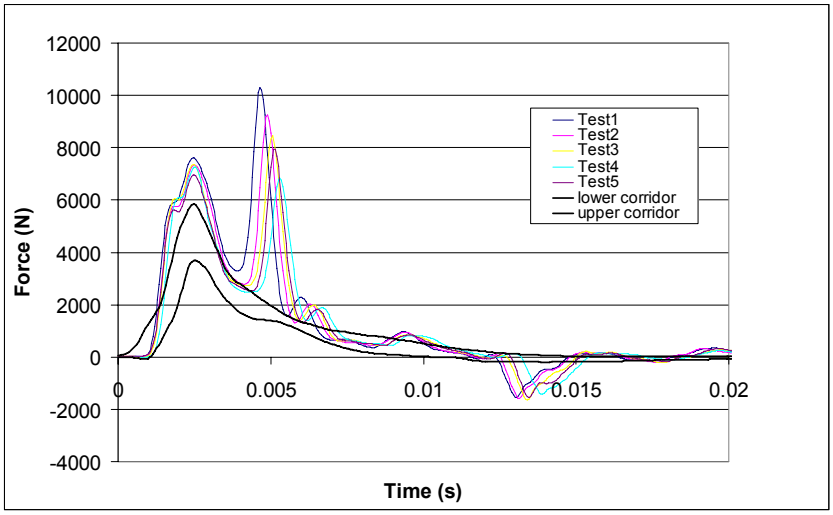

Figure 8: Force-time curves from THOR – Condition 3.

DISCUSSION

Two biomechanical surrogates were evaluated using human response corridors previously developed (Barbir, 2005). The tests of the Hybrid III with a foot/ankle complex showed that the tibia forces measured in the mid-tibia of the cadaver were significantly lower than those measured in the Hybrid III (Figure 6). This is consistent with the findings of both Begeman (1990) and Crandall (1996) during automotive impact events. The additional data gathered from the foot/ankle assembly showed that forces even higher than those found in the tibia were measured at the ankle. This is also consistent with the literature, where the most common injuries noted were in the ankle, namely calcaneus and pylon fractures. However, the reported increase in injuries may also be related to the structure of the ankle and foot complex and susceptibility to injury.

Given the current loading conditions, the tibia structure experienced an average axial loading of more than 4.5 kN. This force is lower than the currently reported tolerances for fracture in the field of automotive impacts, however the goal of the current study was to evaluate the biomechanical responses not elicit injurious levels.

The tests of the THOR Lx showed that at lower conditions (Condition 2), the THOR matches the cadaver data well (Figure 7). However, at more severe conditions (Condition 3), the THOR overpredicts the tibia forces by 25% (Figure 8). The reason for this could be as explained in Ore (1993), that the modulus of elasticity of bone increases with the strain rate raised to the 0.06 power. This implies that the velocity of impact influences the force experienced by the bone. While this holds true for biological tissue it does not hold for the metal shaft of the THOR lower-Lx. That is why THOR-Lx forces match the cadaver forces under lower impact conditions, but not the higher velocity cases.

The double peak displayed in Figure 3 was observed only in Condition 3 for the THOR-Lx. It was noted that this second peak in the lower tibia force corresponded to the timing of the very high peak noticed in the upper tibia force. This finding was explained by examining the design of the THOR-Lx lower limb. The THOR-Lx contains a compliant tibia element which was designed to yield 1.8 cm of travel and 3.6 cm of compression. However, at 3 kN applied force it is already 50% compressed. With the forces in this condition reaching the 7 kN range, the compliant element bottoms out.

In order to further investigate the effects of AV mine blasts on the human lower limb, it is recommended the mode of injury be additionally investigated. Use of hardware that can tolerate higher energy impacts will be necessary in order to match such conditions. Additional cadaver tests at these higher velocity impact conditions will produce new corridors against which surrogates can be compared. Furthermore, patterns in modes of injuries under such impacts can be evaluated. In addition to the instrumented reusable surrogates that are evaluated in this study, frangible legs could yield additional insight into both the force level and the mode of injury. They could also substitute the surrogate instrumentation, which can be impacted above its limit (Manseau, et al., 2005).

CONCLUSION

Two biomechanical surrogates were evaluated in terms of their biomechanical response to simulated AV land mine loading. These responses were compared to PMHS corridors previously developed**.** The differences between the Hybrid III lower limb with a foot/ankle assembly and the THOR Lx show that the THOR-Lx experiences lower tibia forces closer to those found in the PMHS testing. Due to the fact that the THOR-Lx was constructed as a more biofidelic version of the Hybrid III, this is to be expected. However, as reported, the THOR-Lx still does not demonstrate a biofidelic response at the highest loading regimen tested. Further development and research is recommended before an appropriate surrogate for the evaluation of AV landmine injuries can be identified. Next steps will include evaluation of two synthetic frangible surrogates: The Australian FSL (Frangible Surrogate Leg) (Bergeron, 2001) and the Canadian CLL (Complex Lower Leg) (Manseau, 2005a; Manseau, 2005b), originally developed to assess anti-personnel mine protective boots.

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