EVALUATION OF DYMANIC RESPONSE CHARACTERISTICS OF THE MiL-Lx LEG COMPARED TO THE THOR-Lx LEG

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1. Background

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*), the momentum is transferred into the vehicle and this affects the occupants. The response of the occupants is a research topic explored by a number of prominent research intuitions in Europe and USA.

The foot-ankle-tibia region is the primary impact point of an occupant in an underbelly blast event. In addition to being the first region to receive high rate mechanical compressive loading, the lower extremity will experience the most severe peak compressive loads compared to other body region (North Atlantic Treaty Organization TR-HFM-090 2007). Figure 1 highlights the relative magnitude of compressive loading experienced by the lower extremity compared to the lumbar spine and upper neck from an underbelly blast event. Consequently, the lower extremity of a mounted soldier is susceptible to severe injury following a blast event. Although lower extremity injuries may not be an immediate threat to life, many are immediately incapacitating and require long term rehabilitation to decrease impairment.

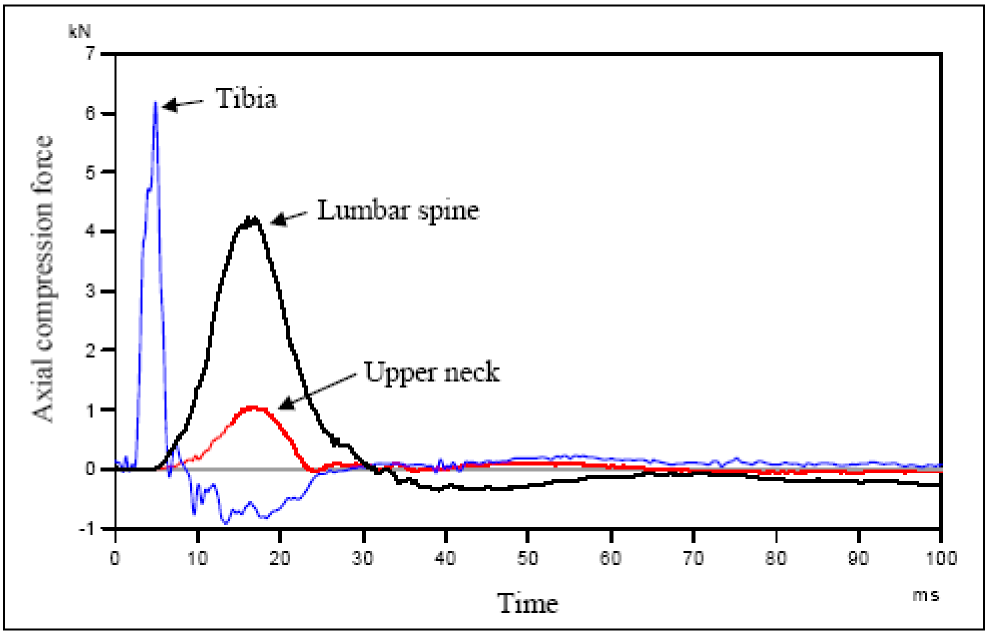

Figure 1: Relative Comparison Magnitude of Compressive Loading on the Occupant in an Underbelly Blast Event (NATO, 2007).

The currently used Hybrid III leg (Figure 2) in the landmine protection research have been developed for assessing the response of the lower leg in vehicle crash safety. This biomechanical surrogate leg has been tested extensively in automotive impacts.

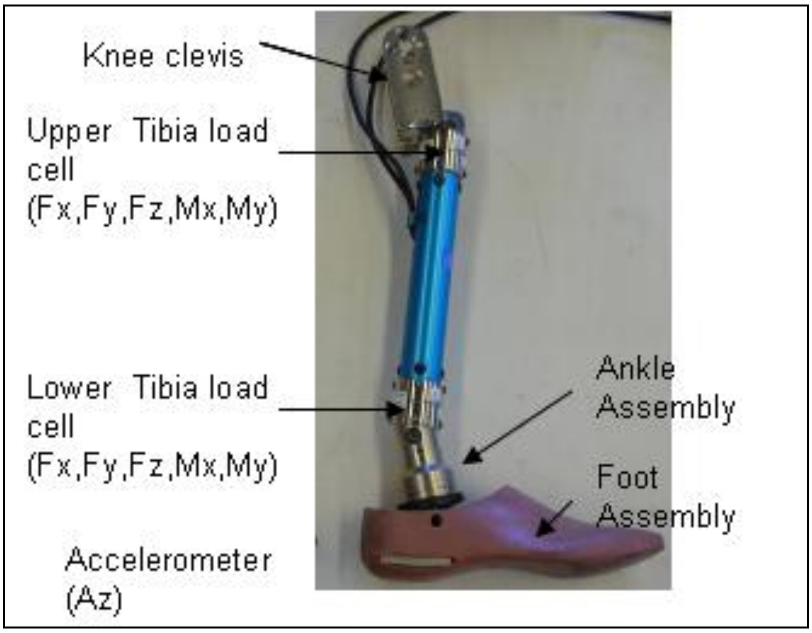

Figure 2: Hybrid III Lower Leg

The currently used AV landmine protection lower limb injury criterion 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

This has resulted in a development of a new lower leg, the Military Extremity (MiL-Lx) leg. The leg was developed collaboratively (using data from GE, CA, SA, NE) between Robert Denton and Wayne State University (WSU) using the WSU test methods and equipment. Figure 3 is a photo of the HFM TG 198 team who contributed to the development of the MiL-Lx leg. 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.

Figure 3: HFM Task Group 198 in South Africa, November 2010

The MiL-Lx leg has been selected for inclusion in the NATO standard. It has been established that there is a lack of data and experience surrounding MiL-Lx leg. 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. The MiL-Lx leg has been tested using the WSU test rig but has never been extensively evaluated using other test rigs. The MiL-Lx leg has never been compared to the THOR-Lx leg.

2. Design of Mil-lx and THOR-Lx Legs

2.1 Test Device for Human Occupant Restraint (THOR-Lx)

Like Hybrid III lower leg, THOR-Lx lower leg assembly (Figure 4) was designed to fit the 50th percentile male Hybrid III ATD. THOR was developed by the National Highway Traffic Safety Administration (NHTSA) (Bergeron, 2001). The design of the THOR-Lx was based on recent biomechanical data which include the guidelines for the basic geometric dimensions of the lower extremity, location of the ankle and subtalar joints and inertial properties of the leg and foot (Rudd et al, 1999). This leg was developed to offer increased biofidelity and measurement capability, compared to the Hybrid III leg, for frontal car crash.

Regarding frontal crash test loads, the THOR-Lx represents the bio fidelity of a human lower leg much better than the Hybrid III leg.

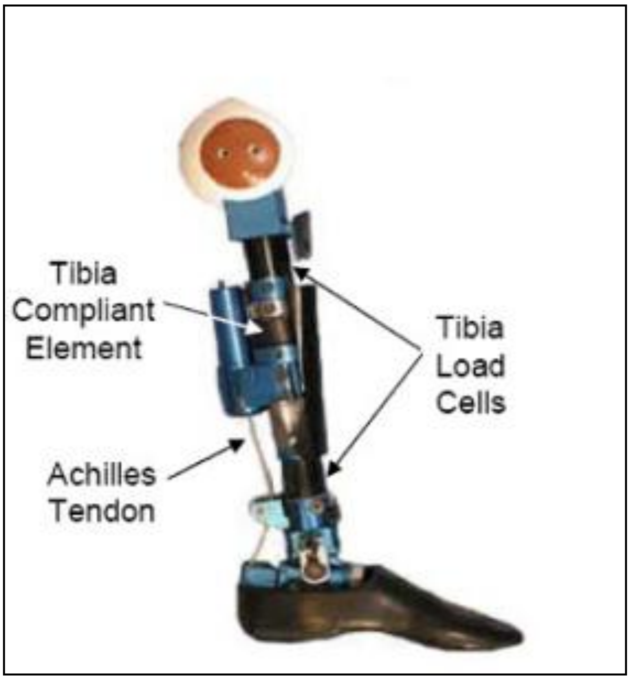

Figure 4: Labelled Thor-Lx Leg (Humanetics, 2011)

The design features of this leg includes:

• A tibia-compliant element to represent compressibility of the tibia for biofidelic axial load response;

• A spring damper Achilles tendon to simulate passive resistance of musculature to dorsiflexion, and to produce the desired ankle motion and torque characteristics;

• A fully functioning ankle that allows rotation in all three directions thanks to separate location of dorsiflexion and inversion/eversion joint centres of rotation represented by the ankle and the subtalar joints, and continuous torque angle joint characteristics. The rotation of the ankle joint about the z-axis (internal and external rotation) has been redesigned to provide a joint torque characteristic which is similar to measured human data.

1.2 Military Extremity (MiL-Lx) Leg

The MiL-Lx (military extremity) leg was designed for impact loading of the foot reflecting the vehicle floor response for condition 4 loads (Humanetics, 2011) and velocities presenting AV mine structural response. The MiL-Lx is a straight leg design with compression-absorbing elements, and optimized for vertical forces and velocities. It is more biofidelic for AV mine loading conditions, simple and robust (Humanetics, 2011).

The core components of the THOR-Lx were utilized in the construction of the MiL-Lx. The THOR-Lx tibia shaft was incorporated into the design of the MiL-Lx because of its human-like geometry. In addition, the THOR-Lx tibia compliant element was also adopted into the MiL-Lx design. The MiL-Lx tibia design aligns the knee pivot, tibia axis and ankle pivot by incorporating a straight knee clevis and straight ankle (Humanetics, 2011).

The compliant element was doubled in length from five to ten centimetres in the MiL-Lx to enable additional room for compression (Figure 5). The longer tibia-compliant element was selected to prevent the full compression (often described as ‘bottoming out’) of the elastomer element at AV blast loading rates. Barbir (2005) fully compressed the compliant element and generated two tibia axial force peaks.

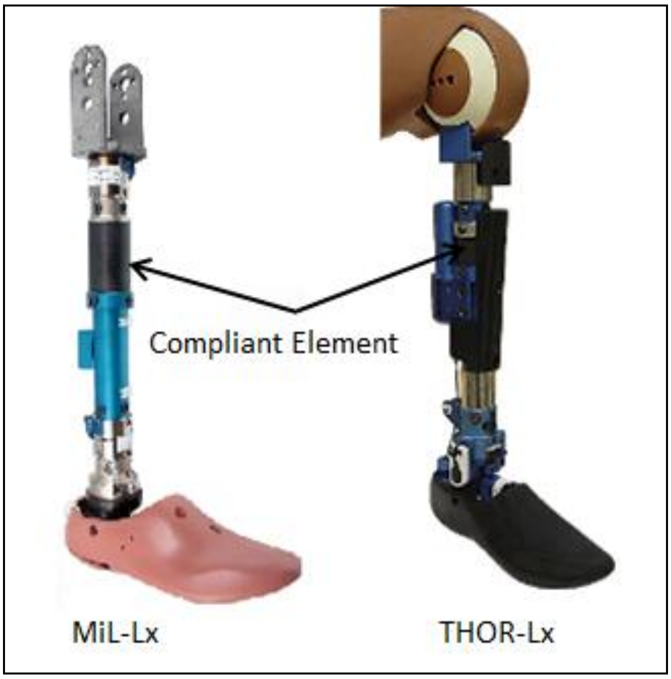

Figure 5: Comparison of MiL-Lx Compliant Element with THOR-LX (Humanetics, 2011)

The compliant element enables the tibia shaft to provide an attenuated force transmission from the heel to the knee complex. The compliant element rests between the upper and lower tibia tubes, which hold the upper and lower tibia load cells respectively. The MiL-Lx tibia shaft includes an accelerometer mounting site distal of the compliant element.

The MiL-Lx foot and ankle closely resembles the structure of the Hybrid III and includes several improvements. The foot has a replaceable rubber energy-absorbing pad in the heel. The MiL-Lx incorporates a more durable polyurethane foot cover than the THOR-Lx and Hybrid III. The cover is expected to enhance the recovery of the elastomer from compression impact to ensure repeatable performance for a longer duration. The cover also includes a slot to install a replaceable compliant footpad. Similar to the tibia-compliant element, the footpad dampens or tunes the force transmission from the heel to the ankle joint and tibia shaft. The bones of the foot are simulated by a carbon fibre plate extending from the heel to the foot. An accelerometer mounting site is located at the mid-foot of the MiL-Lx assembly.

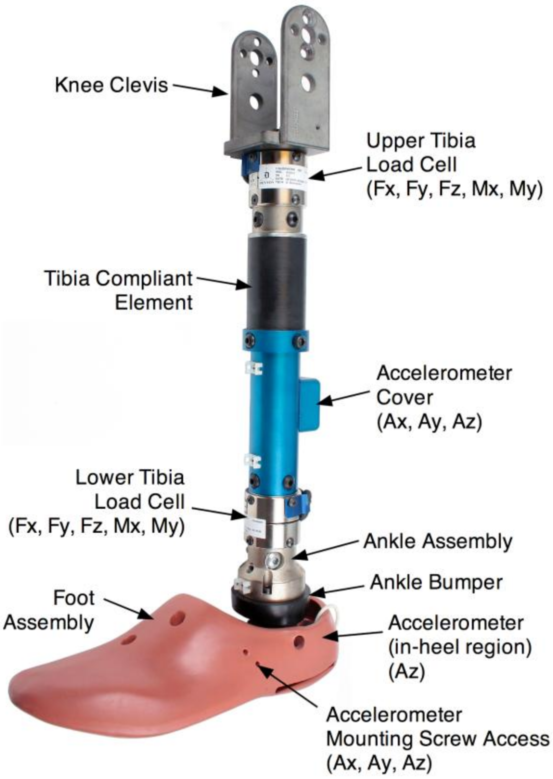

Figure 6: The Military Extremity Leg (MiL–Lx) (Humanetics, 2011)

The Hybrid III ankle ball joint is utilized in the MiL-Lx to simulate the articulation of the foot and ankle. The ankle joint rotates about the x- and y-axes providing inversion / eversion and dorsiflexion / plantarflexion. The joint moment characteristics are controlled by Rosta devices, which increase resistive torque as the joint rotates (Olson, 2007). The ankle joint was designed to reproduce the static and dynamic moment-angle response characteristics in flexion and inversion/eversion measured in PMHS lower limb studies (Olson, 2007).

The ankle is designed to be perpendicular to the sole plate of the foot with the shaft integrated into the foot bone and the ball lowered to closely match the Thor-Lx centre of ankle rotation (Figure 6). Pedestrian knee lower leg attachment blocks are present for added strength and durability.

3. Methodology

Tests were conducted using the Lower Limb Impactor (Figure 7). 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 velocity range from 2.6 m/s to 7.2 m/s. 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.

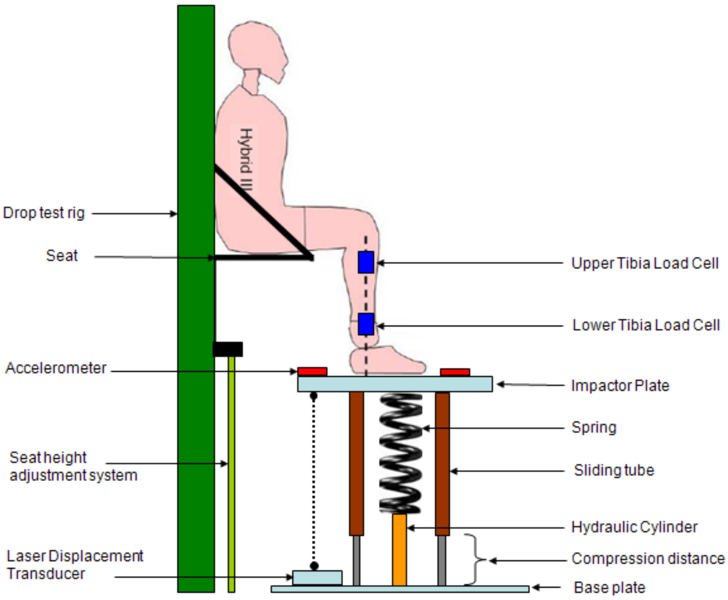

Figure 7: Lower Limb Impactor (Pandelani et al, 2010)

The LLI uses laser displacement transducers to determine the peak plate /impactor velocity. The displacement data was 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 was filtered using a CFC 1 000 filter (NATO, 2007).

4. Results

Since the MiL-Lx leg was designed and validated for impact loading of the foot for peak impact velocities of up to 7.2 m/s on the upper tibia, only the force-time response from this condition is presented.

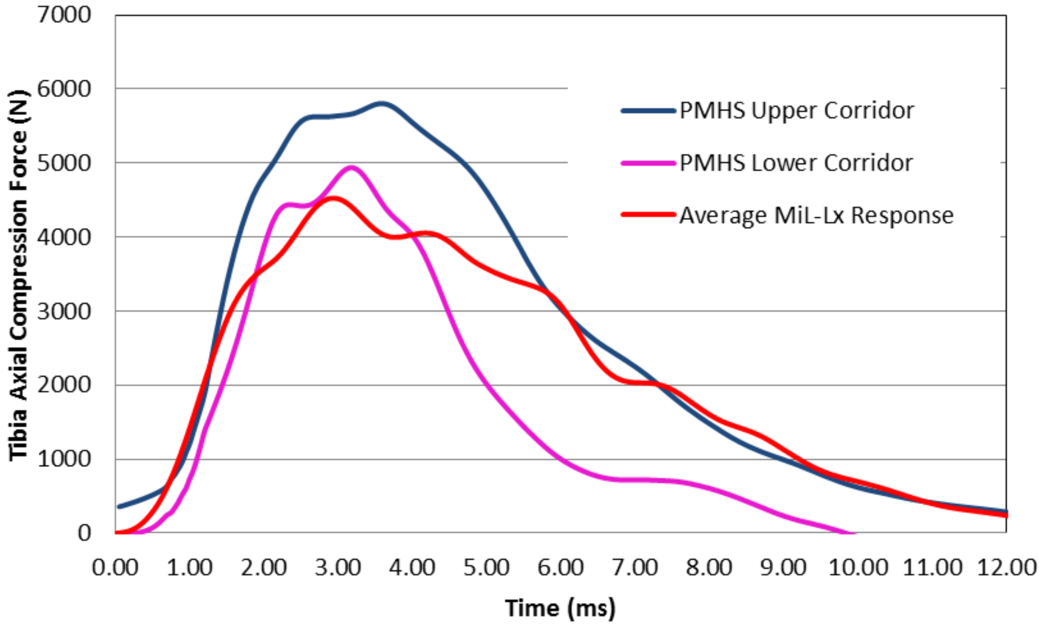

Figure **8** compares the average MiL-Lx upper tibia response with the PMHS non-injury corridor developed by Mckay (2009). The MiL-Lx peak tibia compressive load, loading rate, and duration compare favourably to the PMHS non injury corridor.

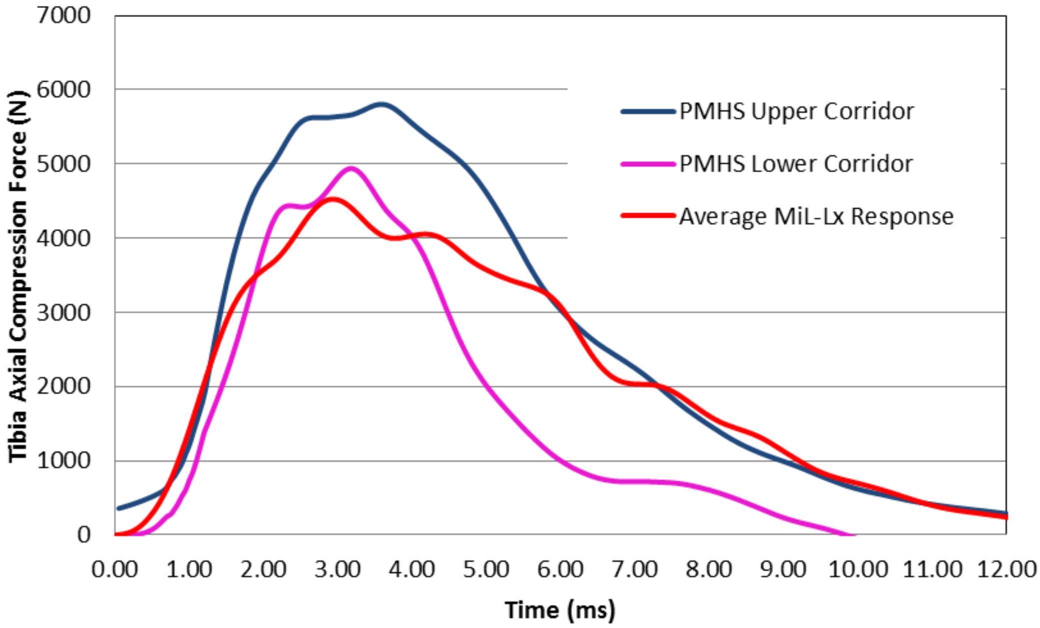

Figure 8: Response of MiL-Lx leg compared to PMHS Non-Injury Corridor

The THOR-Lx averaged upper tibia load was calculated at 6 367 N, which falls outside of the bounds of the corridor constructed from normalized PMHS data for this corridor. The average duration and the loading rates fits within the time range of the established corridor (Figure 9).

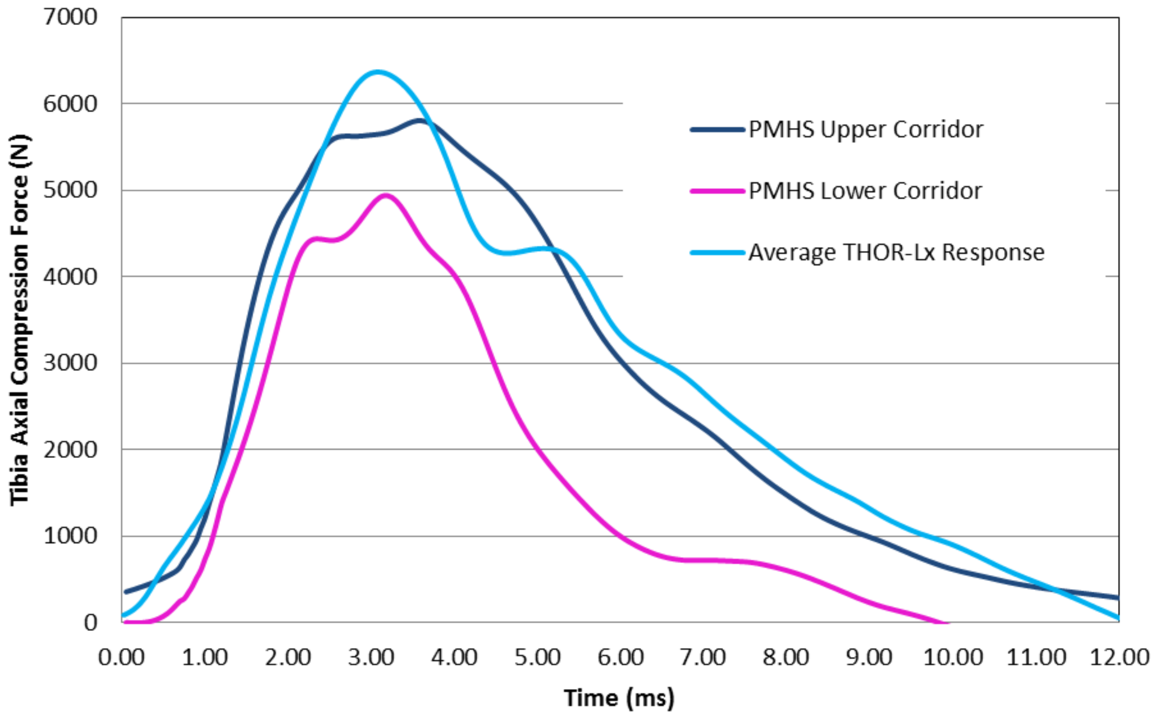

Figure 9: Response of THOR-Lx Leg Compared to PMHS Non-Injury Corridor

5. Discussions

Two biomechanical surrogates were evaluated in terms of their biomechanical response to simulated AV land mine loading. These responses were compared to PMHS corridors recently developed by Mckay (2009)**.** The differences between the THOR-Lx lower limb with a Achilles assembly and the MiL-Lx show that the MiL-Lx experiences lower tibia forces closer to those found in the PMHS testing. Due to the fact that the MiL-Lx was constructed for the AV landmine impacts, this is to be expected. This implies that the MiL-Lx is a more suitable surrogate to evaluate lower limb injuries due to AV landmines.

The Mil-Lx improves the accuracy and sensitivity needed to evaluate blast mitigation technologies designed to reduce injury to occupants of vehicles encountering AV landmines. By giving engineers the ability to assess and implement various countermeasures, occupant lower extremity injuries can be reduced or eliminated.

6. Acknowledgements

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