A NOVEL APPROACH TO THE EVALUATION OF LOWER LEG INJURIES CAUSED BY AXIAL IMPACT: THE COMPLEX LOWER LEG

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ABSTRACT

The lower leg is the most vulnerable body region to anti-vehicular blast landmines. The current available lower leg injury risk models are limited for the application of vehicle mine testing, especially when using the standard Hybrid III lower leg model. The current work was done to evaluate the performance and biofidelity of a frangible lower leg surrogate called the Complex Lower Leg (CLL), for its use in the development of a new injury assessment model specific to vehicle mine testing applications. The CLL showed satisfying results under 'low' and 'high' severity loading conditions. Although the CLL might require some modifications to improve its biofidelity, it is considered to be a good tool to evaluate lower leg injuries sustained by blunt axial impacts.

Keywords: Lower leg, anti-vehicular blast landmines, injury assessment, axial impact, Complex Lower Leg (CLL), Hybrid III.

THE LOWER LEG is the most vulnerable body region to anti-vehicular (AV) blast landmines (Medin et al., 1998, Radonic et al., 2003). Although not life-threatening, lower leg injuries are associated with a high risk of long-term impairment and ending of a military career. The protection of this body region is a priority and thus, an appropriate injury assessment method is required. To develop such a method, Post Mortem Human Surrogate (PMHS) tests are suitable but unfortunately, represent too complex and expensive a test procedure. They are also not possible in many countries. The Complex Lower Leg (CLL), a frangible synthetic human lower leg surrogate, is believed to be a good alternative to PMHS testing. The standard Hybrid III lower leg, equipped with the Denton leg (Robert A. Denton, Inc.), is commonly used to assess vehicle mine protection systems (Durocher et al., 2003, Horst and Leerdam, 2002, Manseau, 2003). The biofidelity of this leg surrogate is known to be quite poor (Owen et al., 2001), rendering the injury assessment not as accurate as it should be. The Denton leg tibia, being stiffer than the human tibia, gives higher axial force values, resulting in an overestimation of the lower leg injury risk. Many authors have developed lower leg injury risk models based on PMHS data (Yoganandan et al., 1996, Griffin et al., 2001, Seipel et al., 2001, Kuppa et al., 2001, Funk et al., 2002b) but only a few studied the difference between PMHS and Hybrid III response (Kuppa et al., 1998, Owen et al., 2001). At this point, foot/ankle injury risk models developed by Yoganandan and Funk are believed the best approach to assess vehicle mine protection systems. But because they were developed in different loading conditions and only based on PMHS response (not Hybrid III response), the necessity of developing an injury assessment methodology specific to AV mine protection testing was identified. The objective of this work was to evaluate the performance and the biofidelity of the CLL for use in the development of this method. The Complex Lower Leg, as well as the Hybrid III lower leg, was subjected to axial impact of different degrees of severity and the results from these tests are presented in this paper.

ANATOMY, LOADING MECHANISMS AND INJURIES

The lower limb (or lower extremity) is divided in four regions: the thigh, the knee, the leg and the foot/ankle complex. The femur is the thigh bone, the patella is the knee bone, the tibia and the fibula are the leg bones, and the phalanges, the metatarsals and the tarsals are the bones of the foot/ankle complex. The tibia is the larger of the two leg bones and bears most of the body weight. In this document, the term lower leg is used to designate the leg and the foot/ankle complex (Figure 1). The tarsal bones (in the ankle) are the calcaneus, the talus, the cuboid, the navicular and the three cuneiforms. The talus, which is the only bone to articulate with the tibia and the fibula, transmits all the forces from the foot to the leg.

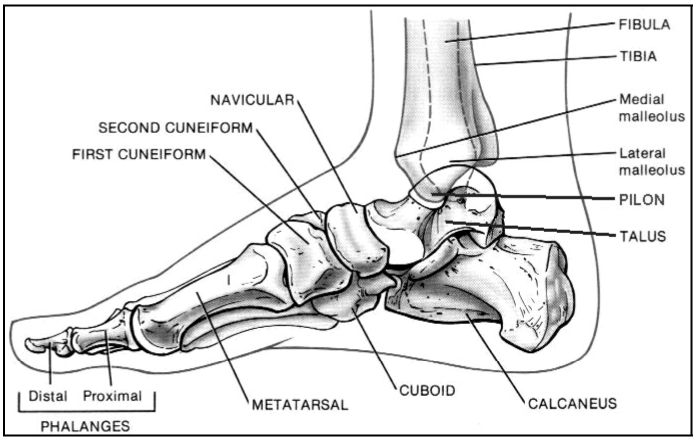


Fig. 1 – Medial view of the right foot (modified from Tortora & Anagnostakos, 1984)

A number of factors will affect the severity of lower extremity injuries resulting from an anti-vehicular blast landmine strike. The most important factor is the distance between casualty and detonation point, which is usually related to the type of vehicle striking the mine. When dealing with light-armoured vehicles, the expected injuries are fractures, dislocation and soft tissue injuries (Medin, 1996) but when dealing with light vehicles (logistic vehicles, cars, trucks, etc.), the severity can be as high as a traumatic amputation (Radonic, 2004). The focus of the present work is on the protection of light-armoured vehicles for which the most expected injuries are fractures in the foot/ankle complex, especially in the calcaneus (Medin, 1996, Radonic, 2004). During a mine strike, the movement of the structure on which the foot rests (floor, driver pedal, etc.) induces an important axial load to the lower leg of occupants. This mechanism is very similar to the one generated during a frontal car impact but usually occurs faster and results in higher load amplitude. Figure 2 shows a typical tibia loading recorded by the Hybrid III during a blast mine detonation under a light-armoured vehicle.

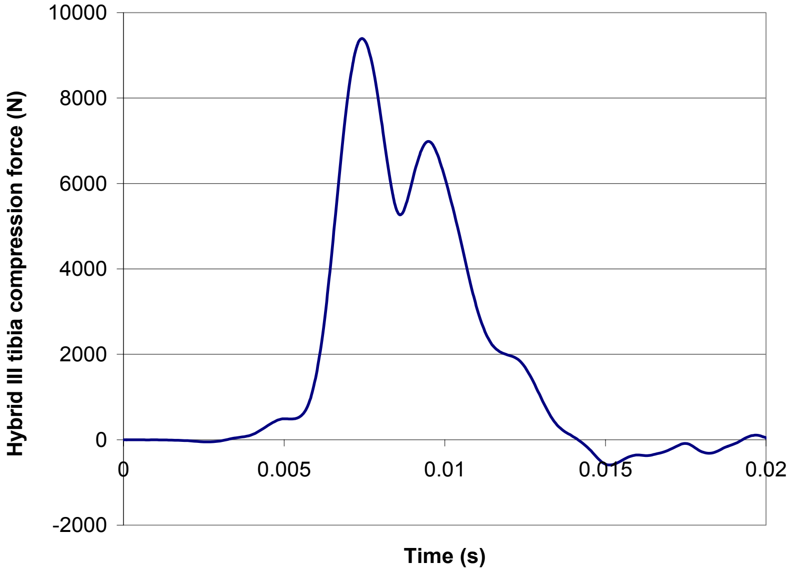


Fig. 2 – Hybrid III axial force recorded during a vehicle mine trial

THE COMPLEX LOWER LEG (CLL)

The Complex Lower Leg (CLL) was initially developed by DRDC Valcartier to evaluate lower leg injuries sustained by antipersonnel mines and is now distributed by Biokinetics and

Associates Ltd. (Williams et al., 2002, Biokinetics and Associates, Ltd., 2003). The leg, shown in Figure 3, is comprised of polymeric bones (that represent tibia/fibula, talus, and calcaneus), a nylon tendon, silicone rubber cartilage pads, a silicone rubber heel pad, ballistic gelatine (representing the flesh), and a latex skin. Since the objective of the CLL was to model the injury path up through the heel into the tibia, the forefoot is not considered and the leg has two calcanei. The total length of the CLL (from heel pad to proximal tibia) is 495 mm.

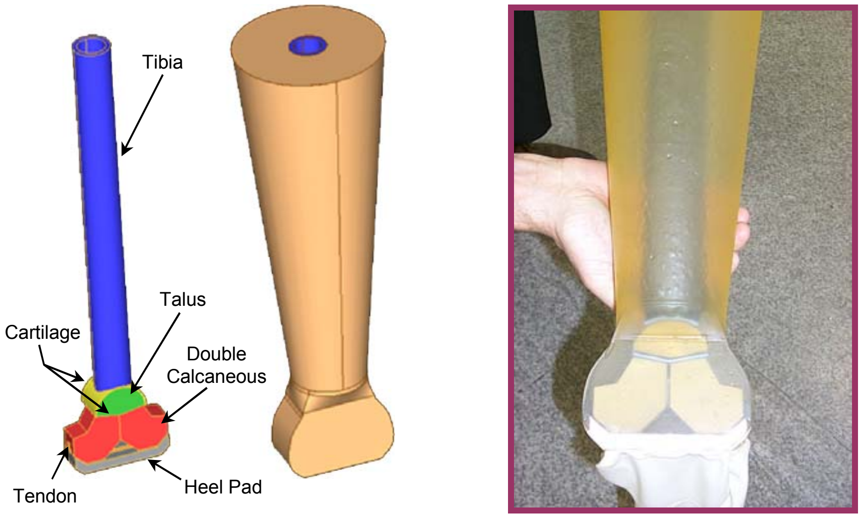


Fig. 3 – The Complex Lower Leg (CLL) and its components (on left) and with its latex skin removed (on right)

The loading generated by the detonation of an anti-vehicular blast landmine is different than that of an antipersonnel blast mine in terms of loading rate, amplitude, duration and resulting injuries. The evaluation of the CLL biofidelity under more realistic loadings was necessary before using it to support the development of an injury assessment methodology for vehicle mine protection testing.

LOW SEVERITY TESTING

METHOD AND TEST SET-UP: To evaluate CLL biofidelity, the approach used was to reproduce PMHS axial test studies of the open literature and compare PMHS and CLL response. The test set-up of Owen (2001) and Funk (2002b) were approximated to test the CLL under non-injurious (Owen) and injurious (Funk) conditions. A standard Hybrid III lower leg was used to set the input conditions for both Owen-style and Funk-style testing. Both the Hybrid III leg and the CLL were tested three times in order to ensure a good repeatability. For both Owen-style and Funk-style testing, the CLL tibia was cut such that the overall length was reduced to 402 mm, in order to have same total length for both leg models. It was assumed that this modification would not affect the biofidelity of the CLL in terms of injury response.

An air cannon and sled/rail system (Figure 4) was set up as an impact test device. A rod was placed inside the air cannon barrel to act as a piston. When compressed air from the tank is exhausted through the air cannon barrel, the piston is forced forwards, pushing against a sled. Using low-friction bearings, the sled rides along two linear rails. When the piston reaches the end of its stroke, the sled is free to continue sliding on the rail towards the intended target. The sled is then arrested by a physical stop or by impact with the target. Different impact anvils can be installed on the front of the sled. The velocity of the footplate prior to the impact was measured with a fibre-optic light gate.

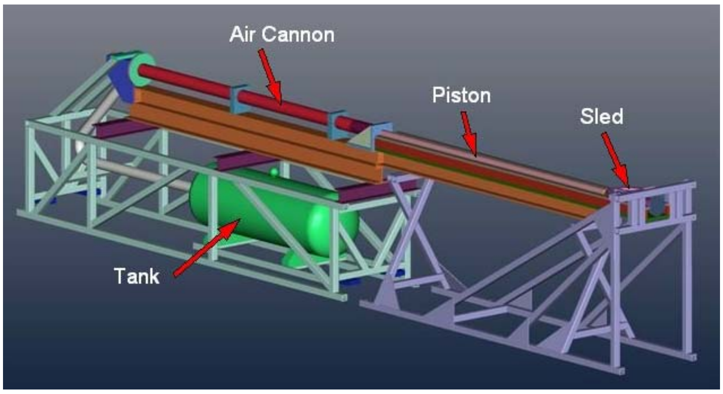


Fig. 4 – The air-actuated piston system

NON-INJURIOUS (OWEN-STYLE) TESTING: The objective of Owen (2001) work was to study the biofidelity of existing dummy lower legs. Four dummy legs (including the standard Hybrid III) were impacted on the heel and toe at different velocities. In the current work, Owen 4 m/s heel impact test conditions were reproduced. Figure 5 presents a photograph of the Owen-style test set-up. A sliding impact head was installed on the front of the sled described above. The size and shape of the impact face was based on the pendulum impact equipment used by Owen. A half-cylinder impact face was used to allow the insertion of steel plates directly behind the impact face for ballast. The total mass of the sliding impact head was 1.5 kg, which was equal to the mass of the Owen pendulum.

For the Hybrid III testing, a femur load cell simulator was secured to the target table and the knee was inserted into the simulator. A footrest was used to provide the correct orientation between the ankle and knee joints. Light grease was applied to the surface of the foot rest to allow frictionless heel movement. The height-adjustable table allowed the leg to be positioned at the correct heel elevation for impact. For CLL testing, an adaptor was designed to allow the connection between the CLL proximal tibia and Hybrid III knee. The proximal end of the CLL tibia was supported by a height-adjustable bracket to ensure the correct heel elevation with respect to the impactor face.

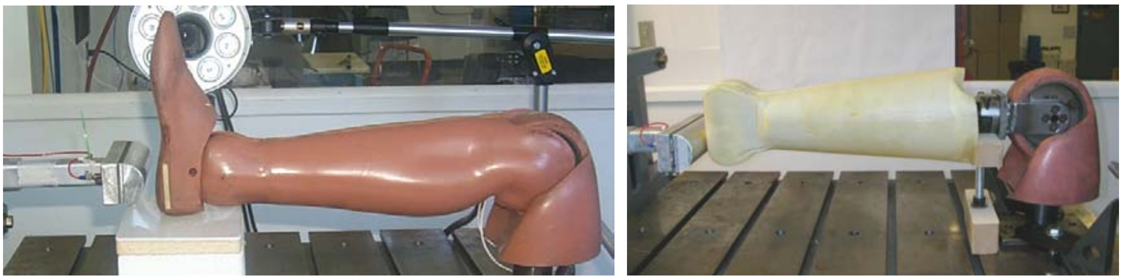


Fig. 5 – Owen-style test Hybrid III (left) and CLL (right) set-up

The input conditions were set such that the Hybrid III tibia axial force gave similar result as in the Owen study. Upper tibia axial force signals were recorded and filtered according to the SAE standard J211/1 (SAE J211/1). Figure 6 shows the target and obtained Hybrid III tibia response. Although the loading duration and the shape of the signal were not the same as Owen's, the peak value and loading rate were very similar, so it was believed that Owen test conditions were well reproduced. To reach this Hybrid III loading, the impact velocity was 5.6 m/s, which was much higher than Owen's impact velocity (4 m/s). This is explained by the fact that Owen used a pendulum set-up, which is subject to different energy losses and momentum transfers than the linear rail system. Figure 7 shows the three tested CLLs, which remain intact (no visible damage) during the testing.

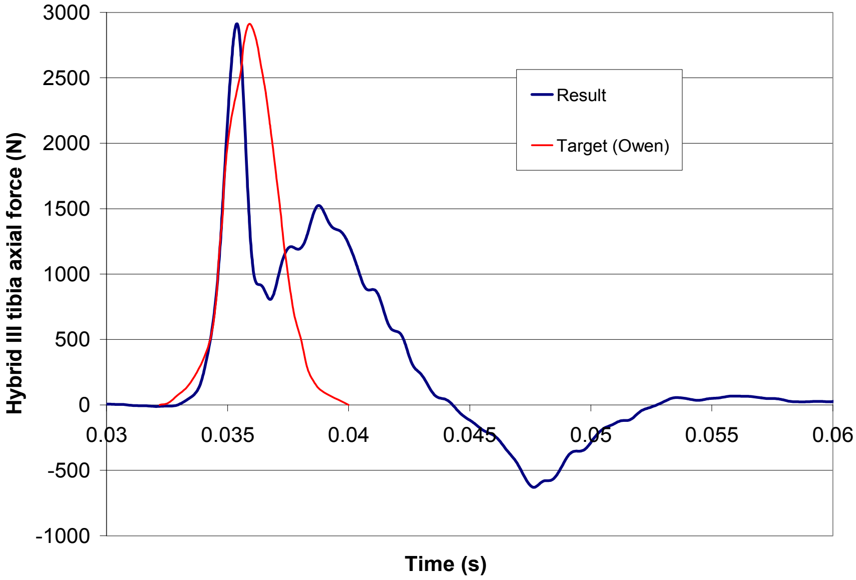


Fig. 6 – Hybrid III response output compared to target response

Fig. 7 – CLLs (with gelatin removed) after Owen-style testing

INJURIOUS (FUNK-STYLE) TESTING: The air cannon and rail system described previously was configured to reproduce the impact scenario of Funk's testing (Figure 8). A rectangular steel plate was secured to the front of the rail sled. Unlike the Owen testing where the impact bar slides out from the sled, the impact plate remains fixed to the sled. The sled/anvil was stopped by the impact with the Hybrid III leg or the CLL. As with the original Funk test set-up, a load cell has been installed directly behind the footplate. The total mass of the impact sled was 18.5 kg. In the original Funk set-up, a layer of foam was attached to the footplate to prevent a direct impact between the foot and the steel plate, although the thickness and compliance of this foam was not specified. In this work, a piece of ¾" VN600 DERTEX foam (vinyl nitrile) was placed on the impact plate.

For Hybrid III testing, the foot was placed on the footrest, which was coated with a light grease, to maintain the correct height. The footrest was placed such that it would not interfere with the initial impact to the foot. The CLL set-up (attached to the Hybrid III knee) was the same as in Owen-style testing. Prior to each test, the Hybrid III or CLL foot was positioned vertically against the impacting plate. In contrast with Funk study, the foot was not in contact with the footplate prior to the impact.

Fig. 8 – Funk-style Hybrid III (left) and CLL (right) test set-up

The input conditions were set such that the Hybrid III tibia response showed a similar loading rate as the PMHS tibia response and a peak value of approximately two times greater than the corridor maximal value. Figure 9 shows the Hybrid III tibia response compared to the PMHS corridor (provided by Funk). These input conditions were obtained with an impactor velocity of 5 m/s and were believed to represent well those of Funk for which the maximum footplate velocity reached an average value of 5 m/s during the testing.

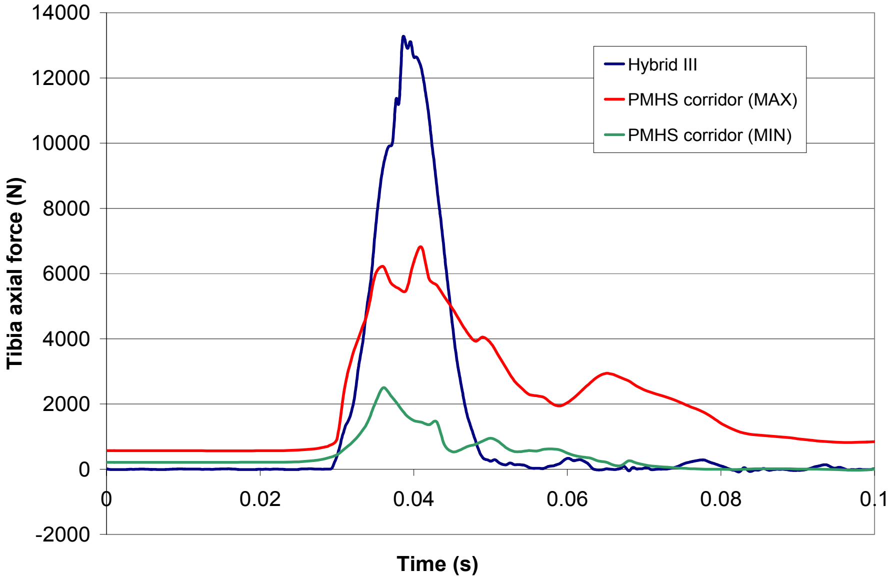


Fig. 9 – Hybrid III response compared to PMHS corridor

The three tested CLLs sustained minor calcaneus fracture and soft tissue injuries (Figure 10). As shown by Figure 10, only the surface of calcaneus bones were damaged, which represents an injury associated with low risks of long-term impairment. Soft tissue injuries are designated by heel pad laceration or cartilage damage. The same injury pattern was observed for each of the three tested CLL, giving confidence that the testing was repeatable. The injuries predicted by the CLL were much less severe than the ones sustained by the PMHS in the Funk study. The PMHS used by Funk were males and females with an age range of 41 to 74 years old, so were not as resistant as the CLL, which is considered representative of a living young male lower leg.

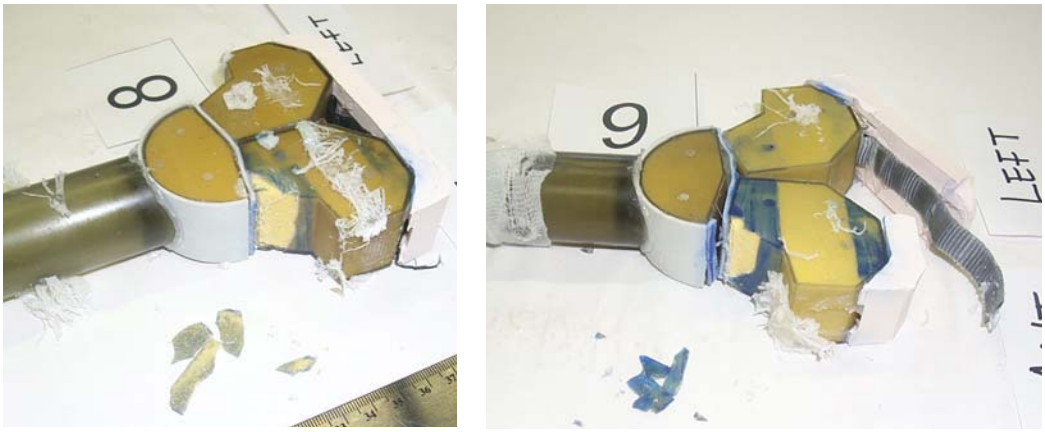


Fig. 10 – Two of the three tested CLLs after Funk-style testing

HIGH SEVERITY TESTING

TEST SET-UP AND METHOD: The same set-up as for Funk-style testing was used to generate higher severity loading conditions. The foam was removed in order to reach a loading representative of loading generated by an AV blast mine, i.e. higher Hybrid III tibia force amplitude and shorter duration. The footplate impacted the foot of the Hybrid III lower leg and the CLL at 5 m/s. Impact tests were also done with a load cell installed at the proximal end of the CLL tibia in order to obtain preliminary results to develop a correlation between CLL and Hybrid III responses. Each of the three tests (Hybrid III, CLL and CLL with load cell) was repeated three times. To prevent slippage of the CLL on the footplate during the impact, sand paper was installed on the footplate. Figure 11 shows the CLL test set-up with its tibia load cell installed at the proximal end. An adapter (red) was designed to install the load cell between CLL tibia and Hybrid III knee adapter. The CLL length was the same as in previous testing giving a higher total length (from Hybrid III knee to CLL foot).

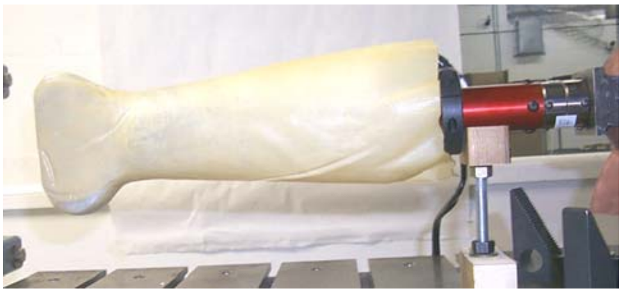
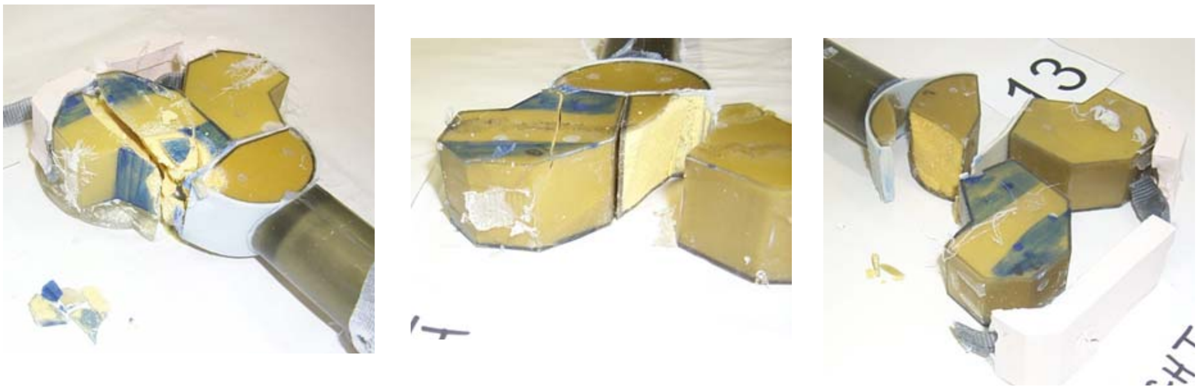


Fig. 11 – CLL set-up with the tibia load cell

RESULTS:

<u>CLL without load cell:</u> Figure 12 shows the resulting CLL injuries after being subjected to mine-style loading conditions. The first and the second tests resulted in same injury pattern and severity, i.e. calcaneus fracture. The third test resulted in an unexpected result, which was a talus fracture without significant calcaneus damage. Based on Griffin (2001) and Funk (2002b) experimental data, talus fracture normally does not occur without calcaneus fracture.



Test 1 Test 2 Test 3

Fig. 12 – CLLs after 'mine-style' testing (without tibia load cell)

<u>CLL with a load cell:</u> Figure 13 shows CLL results for the same loading conditions but with a load cell installed at the proximal end of its tibia. As in the previous testing, the injury patterns and severity were not well repeated. First, a talus fracture again occurred without calcaneus damage (third test) and secondly, one CLL sustained extremely severe damage of both calcanei (second test). The three CLLs were subjected to same impact velocity and high speed video recording of the impact did not indicate any difference between the tests. Also, as shown in Figure 14, the recorded tibia axial force was similar in each test. However, the second test signal suggests a second impact, which could be responsible of this higher injury severity.

Test 1 Test 2 Test 3

Fig. 13 – CLLs after 'mine-style' testing (with tibia load cell)

Fracture of the talus without fracture of calcaneus was never observed during antipersonnel mine testing in which calcaneus, talus as well as tibia were commonly fractured. In this testing, for which the loading was much less severe that antipersonnel mine loading, it seems that CLL mechanical properties are sensitive and may have an influence on the biofidelity of the CLL injury response.

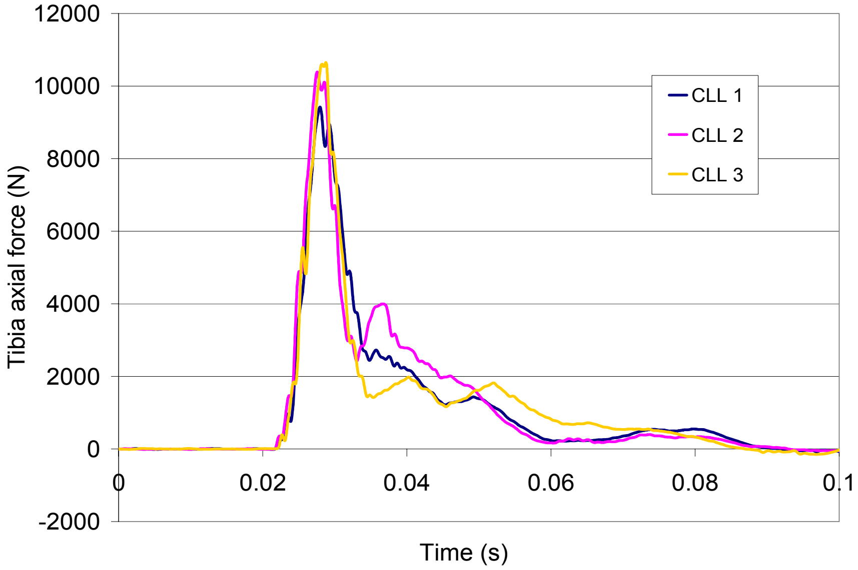


Fig. 14 – CLL tibia axial force for mine-style testing

Comparison between Hybrid III and CLL tibia response: The Hybrid III lower leg was subjected to the same impact conditions in order to compare CLL injury severity and tibia force response with Hybrid III tibia force response. Figure 15 shows both Hybrid III and CLL tibia axial force for this testing. Figure 15 shows the stiffness of the Hybrid III lower leg compared to a more biofidelic surrogate such as the CLL. The tibia force response given by the Hybrid III has a higher amplitude and a shorter duration. When looking to the peak force value, the Hybrid III response is approximately 1.7 times that of the CLL. This result is consistent with similar studies conducted by Owen et al. (2001) and Kuppa et al. (1998). Owen results showed that Hybrid III tibia force was approximately 1.2 to 1.6 times greater that the one measured in PMHS when subjected to (non-injurious) heel impact at 4 m/s. Kuppa, who reproduced Yoganandan (1996) (injurious) axial impact tests on the original Hybrid III lower leg, found a correlation factor of approximately 1.8 for rise times below 55 msec.

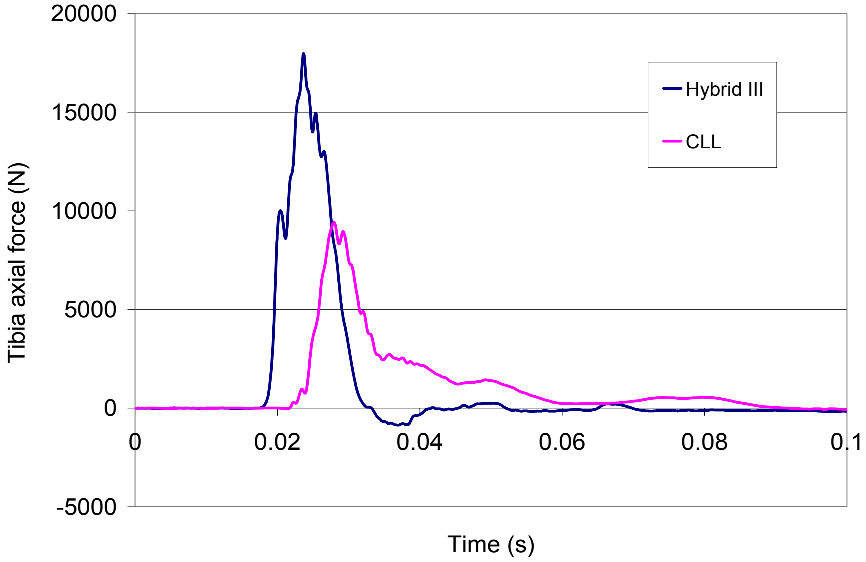


Fig. 15 – Hybrid III and CLL tibia axial force for 5 m/s impact

DISCUSSION AND CONCLUSIONS

The objective of this work was to evaluate the performance and biofidelity the Complex Lower Leg (CLL) under blunt axial impact in order to use it for the development of an injury assessment method for vehicle blast mine testing. The CLL was subjected to non-injurious and injurious axial impacts and compared with Post Mortem Human Surrogates (PMHS) subjected to similar conditions. The results obtained were satisfying and suggested that the CLL is a good representation of a human young male lower leg. Preliminary results were generated to compare CLL and Hybrid III tibia axial force response. The ratio between Hybrid III and CLL tibia force peak values was in concordance with results of other studies (Owen, 2001, Kuppa, 1998). Finally, the tests performed in this study only resulted in foot/ankle injuries without any tibia damage. These results are biofidelic, considering that the foot/ankle complex is the most vulnerable region of the lower leg when subjected to axial impact (Yoganandan, Griffin, Seipel, Funk). However, there was a lack of biofidelity and consistency for foot/ankle injury patterns for 'high severity testing'. Some improvements of CLL bone mechanical properties or assembly techniques might be required before proceeding to the next phase of this project.

The NATO Task Group HFM-090/TG-025 (HFM 090) is now developing an injury assessment method for vehicle blast mine protection testing, which includes injury criteria and acceptable tolerance levels (Manseau, 2003). The tolerance levels are set such that they represent a maximum risk of 10% of AIS 2+ injuries. For the lower leg, the proposed tolerance value is a maximum peak axial force value of 5.4 kN, measured in the standard Hybrid III tibia. This tolerance level is based on PMHS test data generated by Yoganandan (1996). The present work showed that when using the Hybrid III lower leg, the force measured in the tibia can be much higher than 5.4 kN before producing significant injuries. For example, Funk-style testing resulted in minor calcaneus fracture when the Hybrid III axial force was as high as 13 kN. Although this testing was not representative of mine loading conditions, it showed that the current tolerance value might be too conservative and that a correlation between biofidelic leg surrogate and Hybrid III response is necessary. But to develop this correlation, it is believed that not only the tibia peak force value should be considered but also other parameters, such as impulse, loading rate and duration.

In conclusion, this study showed that the Complex Lower Leg has the potential to be a good research tool to evaluate lower leg injuries resulting from axial impact and is a suitable surrogate when PMHS testing is not available. The way ahead for this project, on the development of a lower leg injury assessment method for vehicle blast landmine testing, will include the following steps:

1. Improve CLL material and/or assembly techniques for better biofidelity and reproducibility in severe (anti-vehicular mine) loading regimes;
2. Perform other tests to verify CLL performance and biofidelity;
3. Improve air-cannon system to generate real mine loading and better control input loading conditions;
4. Identification of the parameters having the largest influence on the lower leg injury severity (peak tibia force, loading rate, impulse, etc) under AV mine loading conditions;
5. Development of a correlation between Hybrid III lower leg and CLL responses for AV blast landmine loading regimes.

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