EVALUATION OF THE COMPLEX LOWER LEG (CLL) FOR ITS USE IN ANTI-VEHICULAR MINE TESTING APPLICATIONS

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ABSTRACT

The Complex Lower Leg (CLL), originally developed to assess antipersonnel (AP) mine injuries, was identified as a suitable surrogate to develop an injury assessment methodology for foot/ankle injuries sustained by occupants exposed to anti-vehicular (AV) blast landmines. The objective of this work was to evaluate the CLL performance, with the best available techniques, for its use in a new application: AV mine testing. The approach was to use the standard Hybrid III instrumented lower leg to set the input conditions to which the CLL was submitted. The first part of the work consisted in 'low' severity testing. Owen et al. (2001) and Funk et al. (2002b) studies on Post Mortem Human Surrogates (PMHS) were recreated in order to compare CLL and PMHS responses. The CLL, submitted to non-injurious (based on Owen, 2001) and injurious (based on Funk, 2002b) conditions, showed realistic results. The second part of the study was to test the CLL under 'high' severity loading conditions representative to that of AV blast mine conditions. The results of this second testing suggest that the CLL might require some modifications to improve its biofidelity in terms of foot/ankle injury prediction for these specific loading conditions. Finally, the work also includes the results of the tibia axial force measured with a load cell installed on the CLL for the first time. In conclusion, the Complex Lower Leg showed satisfying results within the scope of the current work and thus, is believed to be a suitable tool to evaluate foot/ankle sustained by anti-vehicular blast landmine.

Keywords: Foot/ankle complex, anti-vehicular blast landmines, injury assessment, axial impact, synthetic leg surrogate, Complex Lower Leg (CLL), Hybrid III.

THE FOOT/ANKLE COMPLEX is the most vulnerable body region of occupants inside a vehicle subjected to anti-vehicular (AV) blast landmines (Medin et al., 1998, Radonic et al., 2003). Although not life-threatening, foot/ankle 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 (Manseau and Keown, 2005, Horst et al., 2005) and thus, an appropriate injury assessment methodology is required. Post Mortem Human Surrogate (PMHS) tests are suitable for the development of such methodology, but unfortunately, represent too complex and expensive test procedures. They are also not possible in many countries. The Complex Lower Leg (CLL), a synthetic human leg surrogate develop for antipersonnel (AP) mine testing, is believed to be a good tool to develop such methodology. The loading generated by the detonation of an AV landmine is different than that of an AP mine in terms of loading rate, amplitude, duration and resulting injuries. For this reason, it is necessary to verify the CLL performance before using it for an application outside the original intention.

INJURY MECHANISMS AND ASSESSMENT

The axial compressive load generated by the detonation of a blast landmine under a vehicle may injure different body regions such as the lower extremities, the spine and the head. A number of factors may affect the severity of AV mine injuries. 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 lower extremity 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). The standard Hybrid III leg, equipped with the Denton instrumented tibia (Robert A. Denton, Inc.), is commonly used to assess vehicle mine protection systems (Durocher et al., 2003, Horst and Leerdam, 2002, Manseau, 2004). Typical tibia loadings recorded during mine tests on light-armoured vehicle (Figure 1) have a duration of approximately 10 to 20 milliseconds and a loading rate of approximately 1.5 to 5 kN/ms. The amplitude varies with the severity of the testing conditions and the performance of the protection system. Because of its reasonable cost and the high risk of equipment damage during vehicle mine testing, the standard Hybrid III leg is widely used by many countries, as opposed to other more recent surrogate such as the Thor-Lx. On the other hand, the biofidelity of this leg surrogate is known to be quite poor, rendering the injury assessment not as accurate as it should be. The Denton tibia, being stiffer than the human tibia, gives higher axial force values, resulting in a possible overestimation of the foot/ankle injury risk.

Many authors have developed foot/ankle injury risk models based on PMHS tibia axial force (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 responses (Kuppa et al., 1998, Owen et al., 2001). 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. The current proposed foot/ankle complex injury tolerance value is 5.4 kN (measured with the standard Hybrid III tibia) and is based on Yoganandan (1996) risk model (Manseau, 2004). Because the Yoganandan model, as well as other similar models, was developed for car crash loading conditions and are based on PMHS tibia response (not Hybrid III tibia response), the necessity of developing an injury assessment methodology specific to AV mine protection testing was identified.

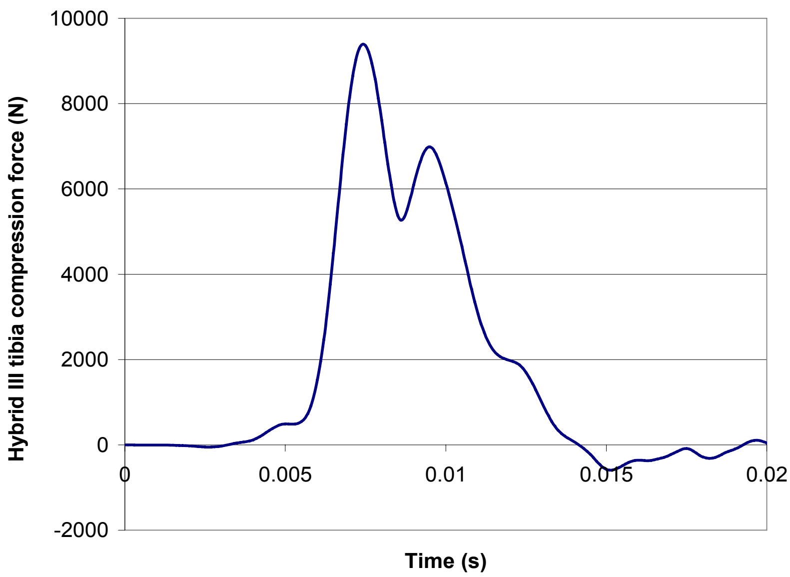


Fig. 1 – Typical Hybrid III tibia axial force recorded during a blast mine detonation under a Canadian light-armored vehicle

THE COMPLEX LOWER LEG (CLL)

The Complex Lower Leg (CLL) was initially developed by DRDC Valcartier to evaluate below knee tibia/ankle/foot complex injuries sustained by antipersonnel mines and assess protective boot performance (Williams et al., 2002, RTO-TR-HFM-089, 2004). The product is now distributed by Biokinetics and Associates Ltd. (Biokinetics and Associates, Ltd., 2003). The design philosophy of the CLL was to create a synthetic surrogate, which could be evaluated using typical medical autopsy procedures to identify the extent and severity of injuries expected in a human tibia/ankle/foot complex. The development of the CLL was based on the selection of appropriate synthetic materials to represent the hard and soft tissues of the human leg and foot/ankle complex. These polymeric materials were selected based on high-rate and quasi-static material properties including failure strengths. The geometry was designed based on the Visible Human Data Base (National Library of Medicine). Care was taken to represent the load paths between the bones, while maintaining simplicity to reduce cost and increase consistency between legs. The name ‘Complex Lower Leg’, refers to the second version of the DRDC synthetic leg called ‘Simplified Lower Leg’ (or SSL), which was the first model developed to evaluate AP mine injuries and protective boot performance (Bourget et al., 2000). A limited correlation of the soft and bone tissue damage predicted by the CLL was made with results from the LEAP program (Harris et al., 2000). The level of mechanical damage to the bones and the soft tissues stripping corresponded well to those observed during tests against PMHS. A finite element model of the CLL also exists.

The Complex Lower Leg, shown in Figure 2, is comprised of polymeric bones (that represent tibia/fibula, talus, and calcaneus), a nylon tendon, silicone rubber cartilage pads, a silicone rubber heel pad, soft tissue, and a latex skin. The soft tissue of the leg is represented by ballistic gelatine. The outer profile of the gelatine is representative of the human leg and foot/ankle complex and ensures a good fit in a boot. Since the objective of the CLL was to model the injury path up through the heel into the tibia, the forefoot was not considered and the model includes two calcanei. The second calcaneus makes the leg symmetric about the two vertical axes and significantly simplifies the tasks of numerical modelling and fabrication. The nylon tendon is bonded to the bottom of the two calcanei, in order to maintain stability of the foot complex. The total length of the CLL (from heel pad to proximal tibia) is 495 mm.

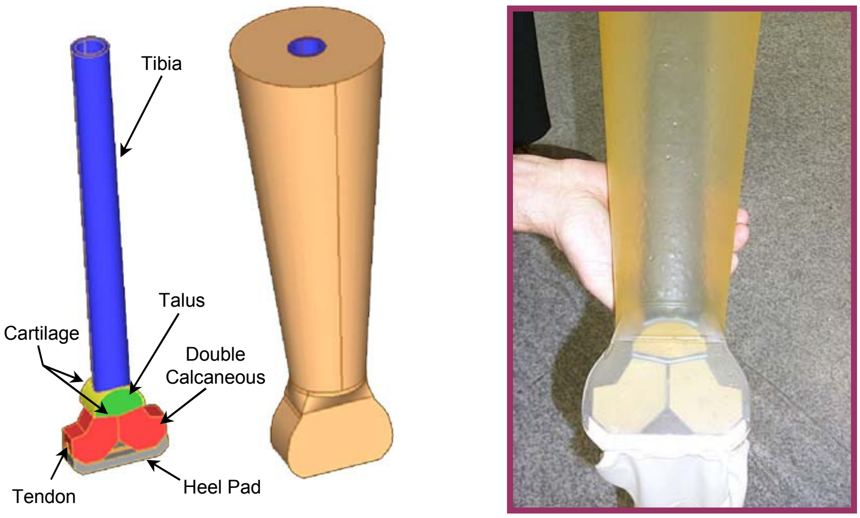


Fig. 2 – The Complex Lower Leg (CLL) and its components (on left) and with its latex skin removed (on right)

‘LOW’ SEVERITY TESTING

METHOD AND TEST SET-UP: To evaluate CLL biofidelity, the first step was to reproduce PMHS axial test studies of the open literature and compare PMHS and CLL responses. The test set-up of Owen (2001) and Funk (2002b) were approximated to test the CLL under non-injurious (Owen-style testing) and injurious (Funk-style testing) conditions. The 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 3) 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 impactor prior to the impact was measured with a fibre-optic light gate. The impactor acceleration was measured for Owen-style testing and the impact force was measured in the case of Funk-style testing. The Hybrid III upper tibia axial force (Fz) and bending moments (Mx, My) were recorded. Only the impactor velocity (measured with the light gate) and the Hybrid III axial force data were used in the current study. The CLL tibia force was not recorded in this testing. All the data were sampled at 20 kHz. The Hybrid III force was filtered in accordance with the SAE J211/1 (SAE J211/1), i.e. Butterworth 4-poles digital filter was used with a cut-off frequency of 1000 Hz (CFC 600). No other post-processing was required.

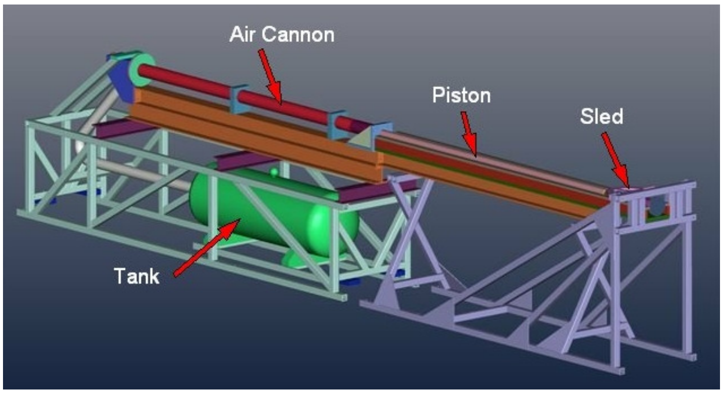


Fig. 3 – The air-actuated piston system

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 4 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 footrest to allow low friction 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.

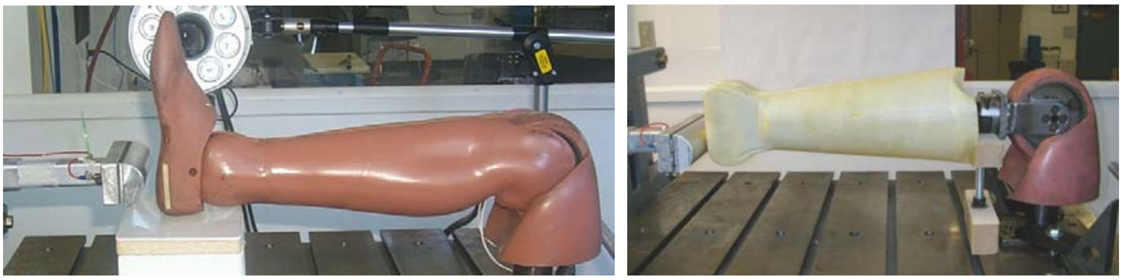


Fig. 4 – Owen-style test Hybrid III (left) and CLL (right) set-up

The input conditions were set such that the Hybrid III tibia axial force gave similar result as in the Owen (2001) study. Although the loading duration and 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 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 5 shows the target and obtained Hybrid III tibia response and Figure 6 shows the three tested CLLs, which remain intact (no visible damage) during the impact.

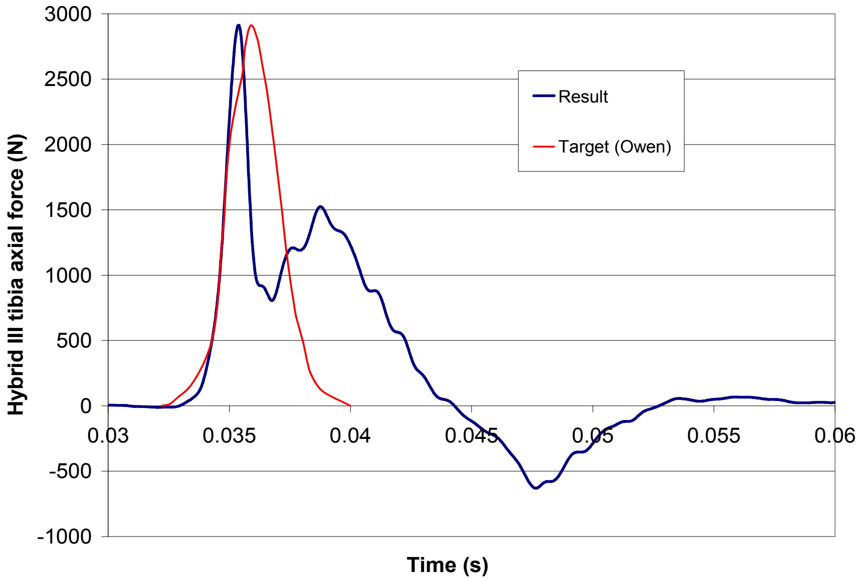


Fig. 5 – Hybrid III response output compared to target response

Test 1 Test 2 Test 3

Fig. 6 – 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 7). 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's study, the foot was not in contact with the footplate prior to the impact.

Fig. 7 – Funk-style Hybrid III (left) and CLL (right) test set-up

The input conditions were set such that the Hybrid III tibia peak force value was approximately two (2) times greater than the PMHS corridor (provided by Funk) maximal value. This ratio between Hybrid III and PMHS tibia peak force was assumed to be realistic, based on previous study of Kuppa et al. (1998). Figure 8 shows the Hybrid III tibia response compared to the PMHS corridor. This was obtained with the impactor velocity of 5 m/s, such as in Funk's study.

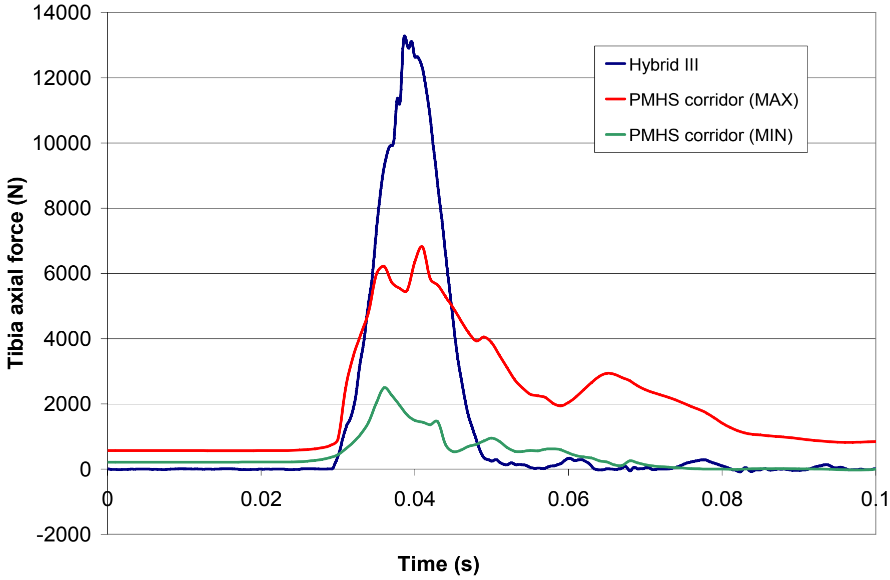
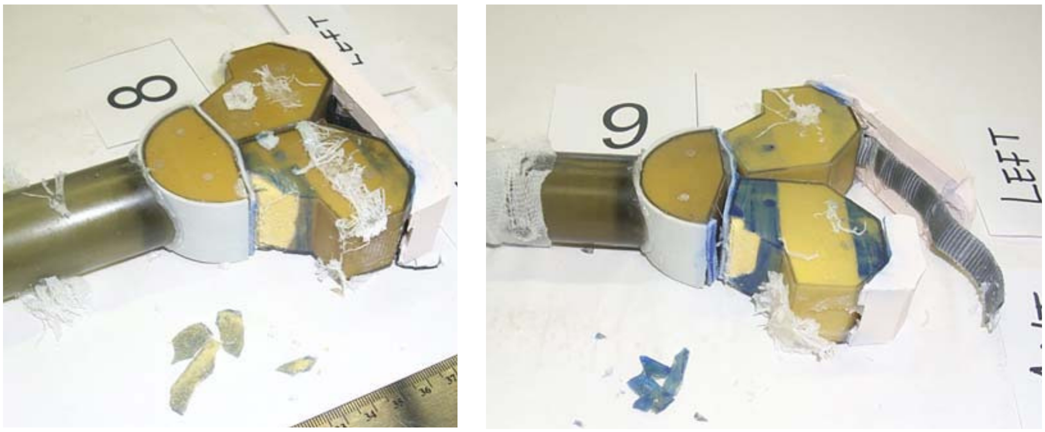


Fig. 8 – Hybrid III response compared to PMHS corridor

The three tested CLLs sustained minor calcaneus fracture and soft tissue injuries (Figure 9). As shown in Figure 9, only the surface of calcaneus bones were damaged, which represents an injury associated with low risks of long-term impairment (Lapointe, 2005). Soft tissue injuries are designated by heel pad laceration and/or cartilage damage. The same injury pattern was observed for each of the three tested CLL, giving confidence that the testing was repeatable.

Based on additional information provided by Funk, it was possible to directly compare CLL and PMHS injury severity. The injuries predicted by the CLL were less severe than those sustained by the PMHS, in terms number of injured regions and injury complexity. In the case of the CLL, only the calcaneus surface was fractured where as the PMHS sustained multiple fractures to the foot/ankle complex, as well as to tibial plateau and fibula (for some of the tests). Also, the fractures sustained by the PMHS were more complex and thus, represented higher risks of long-term consequences and impairment (Lapointe, 2005). This difference between CLL and PMHS resulting injury severity might be explained by the fact that the CLL is more resistant than specimens used by Funk. The second reason for this difference might be the input loading conditions that were not severe enough. The ratio of two (2) between Hybrid III and PMHS force was based on Kuppa (1998) for which the loading conditions were unknown. It is possible that this ratio was not high enough. On the other hand, the injury severity was similar for both surrogates, based on the Abbreviated Injury Scale (AIS, 1990). Indeed, the CLL calcaneus fracture was an AIS 2 injury where as the PMHS injury AIS scores were evaluated at 2 or 3 (Lapointe, 2005).



Test 1 Test 2

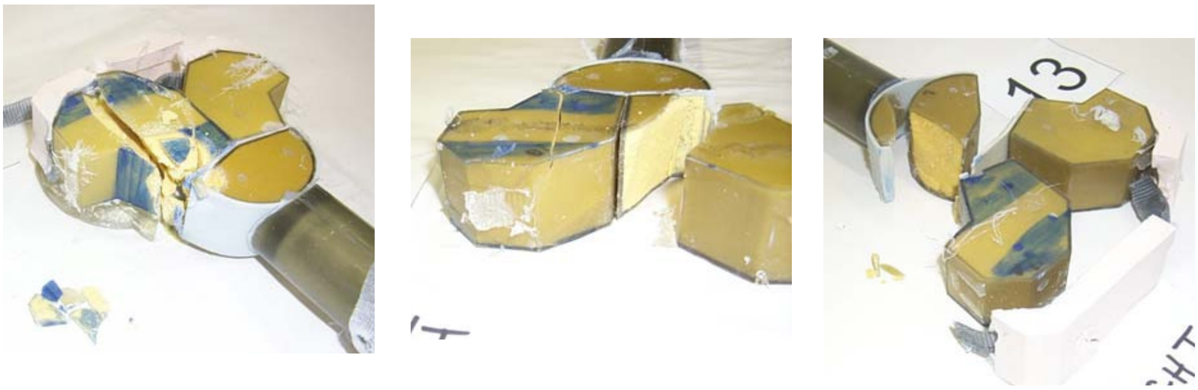
Fig. 9 – Two of the three tested CLLs after Funk-style testing

'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 loading conditions representative of those 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. Tests were also done with a load cell (the one of the Denton leg) installed at the proximal end of the CLL tibia. Each of the three tests (Hybrid III, CLL without load cell 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 10 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). The data processing and filtration methods were the same as in 'low' severity testing.

Fig. 10 – CLL set-up with the tibia load cell

RESULTS: Figure 11 shows the resulting CLL injuries after being subjected to 'high' severity 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. Talus fracture without calcaneus failure was never observed during antipersonnel mine testing in which calcaneus, talus as well as tibia were commonly fractured. In these specific loading conditions, which are less severe that the ones generated by AP mines, only the foot/ankle is injured. Based on Griffin (2001) and Funk (2002b) studies on PMHS, and Lapointe (2005), talus fracture normally does not occur without calcaneus fracture.



Test 1 Test 2 Test 3

Fig. 11 – CLLs after 'high' severity testing (without tibia load cell)

Figure 12 shows CLL results for the same loading conditions but with a load cell installed at the proximal end of its tibia and Figure 13 shows the recorded CLL tibia axial force for each of the three tests.

Test 1 Test 2 Test 3

Fig. 12 – CLLs after 'high' severity testing (with tibia load cell)

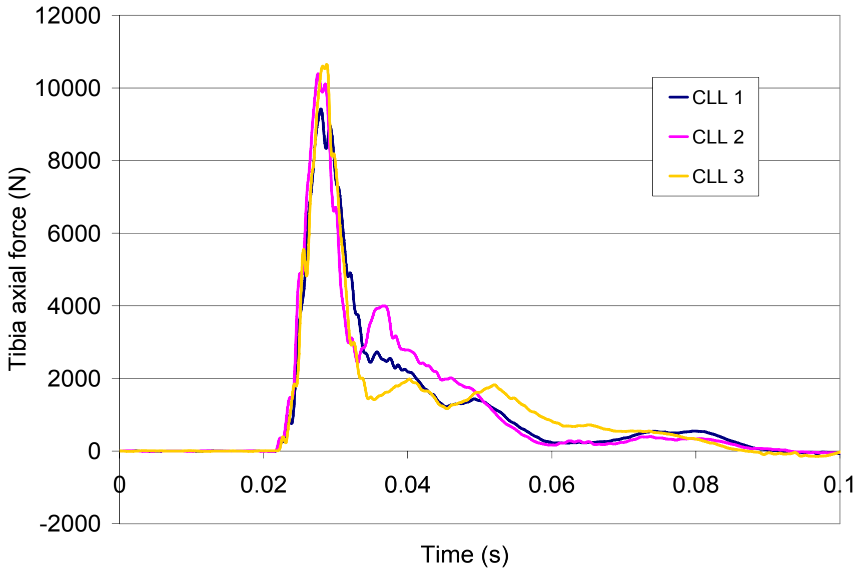


Fig. 13 – CLL tibia axial force for 'high' severity testing

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 13, 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.

Finally, Figure 14 shows both Hybrid III and CLL tibia axial force recorded under 'high' severity conditions. This figure shows the high stiffness of the Hybrid III lower leg compared to a more biofidelic surrogate such as the CLL. Indeed, 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. Owen et al. (2001) and Kuppa et al. (1998) also obtained a ratio of more than 1.0 when comparing PMHS and Hybrid III tibia force responses, however the loading conditions for which these ratios were developed, were different (for Owen) or unknown (for Kuppa). Finally, results presented in Figure 14 suggests that a tibia force of approximately 10 kN for the CLL and 17 kN for the Hybrid III, is required to cause significant fracture to the foot/ankle complex.

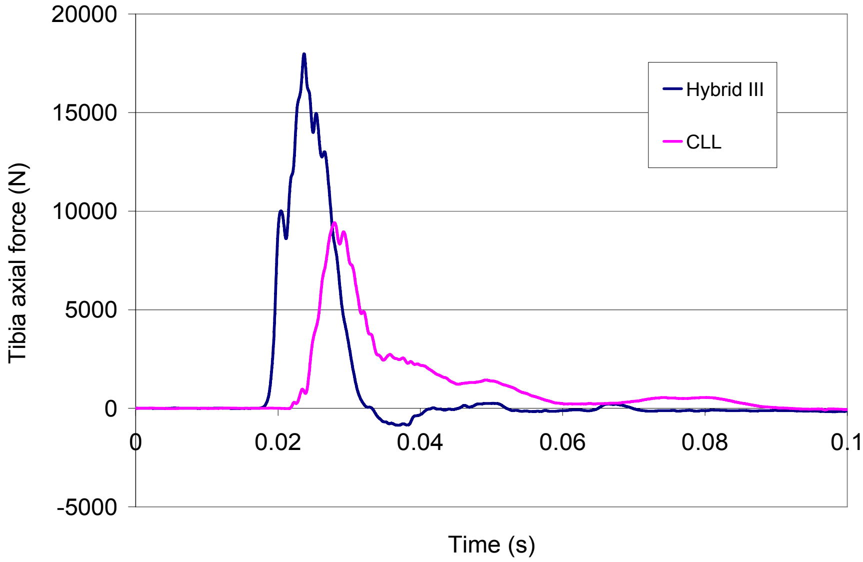


Fig. 14 – Hybrid III and CLL tibia axial force for 'high' severity testing

DISCUSSION AND CONCLUSIONS

The objective of this work was to evaluate the performance of the Complex Lower Leg (CLL) for its use in the development of an injury assessment methodology for vehicle occupants exposed to anti-vehicular (AV) blast mine testing. The CLL was initially developed by DRDC Valcartier, for the specific application of antipersonnel blast mine testing. The scope of the current work was to verify its performance when using it outside its original purpose. To assess the CLL performance, the work included 'low' and 'high' severity blunt axial impact testing.

The first part of the work ('low' severity testing) consisted in reproducing non-injurious and injurious testing conditions of Owen et al. (2001) and Funk et al. (2002b) in order to compare CLL and Post Mortem Human Surrogate (PMHS) responses. Both non-injurious (Owen-style) and injurious (Funk-style) testing gave satisfying results. The second part of the study ('high' severity testing) consisted in testing the CLL under loading conditions similar to that of AV blast landmines. CLL tests with and without load cell showed a slight lack of consistency in terms of foot/ankle injury patterns. This suggested that the foot/ankle bone mechanical properties might require a review in order to improve the biofidelity of the CLL under these specific loading conditions. The problem will be addressed in the next phase of the project. Finally, the addition of the load cell on the CLL tibia was a success in terms of results repeatability.

The current work suggests that the actual foot/ankle injury tolerance value (5.4 kN measured with the standard Hybrid III tibia) used to assess vehicle mine protection systems, might be too conservative. For example, Funk-style testing resulted in minor calcaneus fracture when the Hybrid III axial force was as high as 13 kN. The results showed that the development of a correlation between a biofidelic leg surrogate and Hybrid III response is necessary. It is known that PMHS testing would be the best solution to develop such correlation, but the CLL frangible leg surrogate is presently the best solution available for DRDC. This study showed that the Complex Lower Leg has the potential to be a good research tool to develop a foot/ankle injury assessment methodology specific to vehicle mine testing. The next steps of this project on the development of this methodology, will be the following:

1. Improve CLL material and/or assembly techniques for better biofidelity and reproducibility in severe (AV mine) loading regimes;
2. Perform additional tests to verify CLL performance and biofidelity;
3. Improve air-cannon system to better control input loading conditions;
4. Identification of the parameters having the largest influence on injury severity (peak tibia force, tibia 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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