Test Methods for Protective Footwear Against AP Mine Blast

Duane S. Cronin
Department of Mechanical Engineering, University of Waterloo
200 University Ave. West, Waterloo, Ontario, Canada N2L 3G1

Kevin Williams
Defence R&D Canada – Valcartier, Weapons Effects Section
2459 Pie-XI Blvd. North, Val-Belair, Quebec G3J 1X5 CANADA

C.R. (Dale) Bass
University of Virginia, Center for Applied Biomechanics
1011 Linden Avenue 22903, Charlottesville VA USA

Pascal Magnan
French-German Research Institute of Saint-Louis (ISL)
5, rue du Général Cassagnou, PO Box 34, F-68301 SAINT-LOUIS Cedex

Frank Dosquet
Technical Center for Weapons and Ammunition
WTD 91-460 BWKZ: 2422 PO Box 17 64

Denis M. Bergeron
Defence R&D Canada, currently stationed at
Defence Science & Technology Organisation
Edinburgh, SA 5111, Australia

Jan L.M.J. van Bree
TNO Prins Mauritis Laboratories
Lange Kleiweg 137 P.O. Box 45, 2280 AA Rijswijk, The Netherlands

Abstract

The testing and development of protective footwear for anti-personnel landmine blast threats is of great importance to civilian and military deminers, and peacekeepers. This study will review the wide range of test methods that have been developed by NATO countries to test footwear against the effects of anti-personnel blast mines.

Experimental testing requires the definition of a threat and a means of assessing the expected trauma to the human leg. The latter is accomplished with various physical models to represent the human leg. These models include simple metal columns, mechanical legs, frangible legs and biological specimens. Each model has advantages and disadvantages, and the choice must be guided by the scope and purpose of a given test series. In some cases, it is necessary to use a frangible model, but there are many cases where using a non-frangible model may be more appropriate.

In addition to the physical test methods, computer modelling is providing a powerful tool to analyse and interpret test results. Advances have been made recently with respect to numerical code applications and some applications will be presented.

This paper is one of four related multi-national papers, which are being presented by the members of the NATO HFM-089/TG-024, to address all aspects of the TG-024 mandate related to the testing of protective footwear against the effect of AP blast mines.

Introduction

It is estimated that more than 360 different types of mines have been deployed worldwide (Joss 1997, Velin 1995). Anti-personnel landmines typically contain 28 to 500 grams of explosive and fall into two categories: blast and fragmentation. Fragmentation mines include stake mines, directional mines, and bounding mines and will not be addressed in this report. Blast mines, which rely on the overpressure from the detonation of a high explosive to injure the victim, are the cheapest and most common form of landmine. Additional injuries may also be incurred from environmental fragments such as aggregate in the soil. A typical blast mine consists of an explosive charge, detonator and a mechanical device to trigger the detonator. Blast mines are surface or subsurface buried, and are pressure activated. They are typically designed to injure the target; however, mines with larger charges can be lethal. Buried blast mines are the most difficult to detect and are likely to remain buried for a long period after a conflict (Coupland, 1997).

The threat of anti-personnel landmines to civilian and military deminers is significant. As such, the evaluation and comparison of protective equipment is of particular importance to many countries throughout the world. Over the past several years, many different techniques and protocols for testing protective equipment have been developed. NATO Task Group HFM-089/TG-024 was initiated to review the various methods currently in use and to define testing guidelines that would ensure test results from different nations are meaningful and comparable.

While a variety of test protocols are currently being used, there are three basic approaches that can be defined by the surrogate used to represent the leg. Common surrogates include mechanical, frangible (synthetic), and cadaver representations or models of the living human leg. All approaches include explosive testing in a controlled environment. One goal of the NATO Task Group has been to investigate the current test methods for protective footwear, and to identify the benefits and limitations of these various test methods.

The selection of a particular test method is determined by the desired level of detail and information required from a particular test. For example, it may be desirable to screen a wide variety of protective footwear and select the best devices for further consideration. In this case, a cost-effective and simple test technique that will provide a relative ranking of performance is appropriate. In contrast a more detailed surrogate, with additional complexity and cost, may not be appropriate for initial testing. However, if detailed information regarding performance and the level of trauma is required, a more detailed test method must be considered. In all cases, there are trade-offs between cost, level of detail available from the test, and ease of testing.

The selection of a test methodology is further complicated since it must be practical to implement by a wide range of users, including many countries with varying ethical constraints and preferences, while providing useful and understandable information. Most important, the final outcome must represent the level of injury incurred for a given threat/protection combination. In general, a test methodology must address four issues:

- Consistency and repeatability.
- Transferability, or the ability for many users/countries to implement and use the test methodology.
- Ability to rank protection for various threat levels based on injury outcome.
- Correlation to expected level of trauma for a given situation.

The relative importance of each issue is tied to the desired outcome from the testing. For example, initial screening of various protection designs may be accomplished with a simple, low cost approach. Alternatively, accurate measurement of performance and trauma evaluation may require a more detailed and typically more expensive test method. To this end, the NATO Task Group has identified three testing categories: screening (mechanical legs), proofing (frangible legs) and validation (human cadavers).

Current test methods incorporate several common elements including: threat definition, a representation of the human leg, means of evaluating the effectiveness of the protection, and of course the protection to be evaluated (Figure 1).

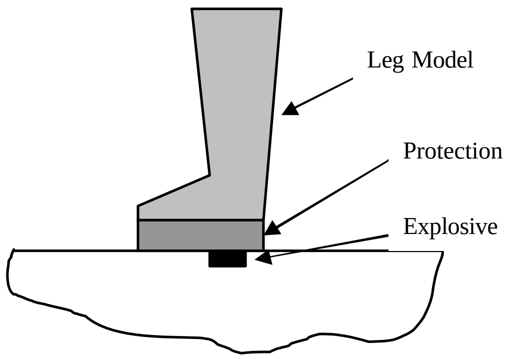

Figure 1 Schematic of a typical test for protective footwear

Threat definition

The threat definition may appear to be straightforward on first consideration; however the consistency of any real landmine can vary significantly in terms of explosive output (LEAP, 1999). This is due to inconsistent amounts of explosive in some mines as well as the possibility of a deflagration versus a detonation of the energetic material in the mine. Further, the Ottawa treaty has limited the availability and transport of real landmines, making it difficult to access real mines as test devices. Nevertheless, it is useful to examine the types of mines encountered to identify the expected threat. AP blast mines currently deployed in the world range from explosive charge masses of 28 grams to 250 grams. Blast mines are typically classified in terms of small (less than 50 grams of explosive), medium (50 to 100 grams of explosive) and large (greater than 100 grams of explosive). The most common explosive used in blast mines is TNT, with Composition B, RDX, and other explosives being less common.

The observed inconsistency in explosive output of real landmines and the difficulty in acquiring them, make them generally unsuitable for experimental testing. However, it should be noted that final proofing of protection may require testing with real threats. In terms of general experimental testing, an explosive that is readily available, easy to work with and generally consistent in terms of detonation and explosive output is desirable. To this end, composition C-4 (91% RDX + 9% nonexplosive plasticizer by weight) and PE-4 (88% RDX + plasticizer) have been used by several countries for experimental testing. It is important to note that there are several differences between C-4/PE-4 and common blast mine explosives. First, the detonation velocity of C-4/PE-4 (8193 m/s) exceeds that of TNT (6930 m/s) (Dobratz, 1980), which leads to a locally increased shock or shattering power, known as brisance. In addition, mid-field measurement of the explosive output of C-4/PE-4 is found to be approximately 1.4 times that of TNT (Kinney, 1962). This must be considered when evaluating protection with a specific C-4 or PE-4 charge.

AP mines are buried flush with or just below the surface of the ground, which has a significant effect on the behaviour of the explosion. Bergeron et al. (1998) conducted experiments with surrogate mine charges consisting of 100g of C-4 explosive. The depths of burial (DOB) considered were 0 mm, 30 mm, and 80 mm where the DOB is measured from the soil surface to the top of the charge. It has been found that a consistent DOB is critical to providing consistent experimental results. Additional research by Bergeron and Tremblay (2000) has shown that soil conditions and explosive confinement significantly affect the impulse from a blast mine on a target. In general, an increase in soil moisture content results in a larger amount of energy transfer from the mine to the target above the mine. Thus a consistent test method requires a single well defined soil that is readily available in many countries One common material that is widely available and can be well characterised is sand. It should be noted that a specific granularity, density, and moisture content are all needed to provide a consistent energy release and pattern of momentum transfer to the boot concept being tested.

A significant portion of any test methodology includes the test protocol and threat definition. The primary goal of the protocol is to create representative, controlled and repeatable test conditions.

Assessment of injury

The testing and evaluation of protective footwear requires specific evaluation criteria. Of utmost importance for a given protection/threat combination is the medical outcome related to injury, required level of amputation (if any), and the long-term prognosis for the patient. With respect to the definition of a test method, it is necessary to relate the measurable quantities from a particular experimental approach to expected medical outcome or severity of injury. For example, tests using a full body cadaver model can be evaluated by means of an autopsy to relate mechanical damage to expected trauma (Lower Extremity Assessment Program, 1999). However, in the case of a reusable mechanical leg, alternate parameters such as acceleration and impulse must be correlated with injury and trauma. It should be noted that, in all cases the true medical outcome must be inferred from the visible mechanical damage including tissue disruption, bone fracture etc. The currently available models do not allow for physiological assessment, including certain aspects of nerve and arterial damage, as well as non-viable tissue.

Clinical experience (Holland and Chaloner 2000; Coupland 1993) with typical landmine injuries indicates that the primary injuries occur in the foot, ankle and lower tibia. As such, it is important that the model be able to assess the response of the leg in this region. Several medical scales currently exist to evaluate mine trauma to a human leg. Surgically-based medical assessment scales, such as the Mangled Extremity Scale (MES) (Gregory et al., 1985) are useful for field evaluation and treatment of injuries. However, the scientific comparison of various levels of protection often requires more detail in terms of damage to the leg (Harris et al., 1999). This was the motivation for the development of the Mine Trauma Score (MTS) (Lower Extremity Assessment Program, 1999), which is specific to AP mine blast injuries of the lower limb. This scale is applicable to frangible and cadaver leg models, which can be evaluated by means a post-test examination. However, mechanical legs require alternate means of evaluation. Load cell, strain gauge, accelerometer, displacement transducer, and high-speed video data can be used to record the response of the leg and to provide a relative comparison of the tested protection. Griffin et al. (2001) have shown that some of these parameters can be correlated with bone fracture and trauma level.

In general, the assessment of trauma, or protection performance, must be evaluated using measurable and/or observable quantities related to the specific test device. As such, the expected accuracy of the evaluation increases from mechanical legs to frangible legs and finally to human cadaver models.

Re-usable test devices (Mechanical Legs)

The category of re-usable test devices includes a wide range of mechanical leg representations that are designed to reflect the mass and dimensions of the human leg, while being rugged enough to survive explosive testing. Since these devices are intended to be re-usable, and blast testing can result in aggressive loading, these devices are commonly constructed out of rigid materials such as steel. The motivation for this approach is that explosive experimental testing tends to be very time consuming and expensive, making a re-usable test device desirable from both a cost and efficiency perspective. Historically, mechanical legs were one of the first common forms of protection testing, with this type of leg being used by the Netherlands (van Bree, 2000), United Kingdom (Holland and Chaloner, 2000, Roberts, 2000), United States (Harris et al., 2000) and Canada (Coffey et al., 1999).

<u>Netherlands Mechanical Leg</u>

As an example, the mechanical leg designed in The Netherlands (van Bree, 2000) evolved from several simpler versions. The first version consisted of a simulated leg using metal tubes to represent the upper and lower leg, with the knee being modelled as a simple mechanical joint. The volume between the metal foot and protection was filled with gelatine to simulate the surrounding soft tissue of the foot and lower leg. The response of the leg was measured using high-speed imaging. The next development included the adaptation of a HYBRID-III crash test dummy lower leg (Figure 2) to this application, including accelerometers to monitor the response of the leg.

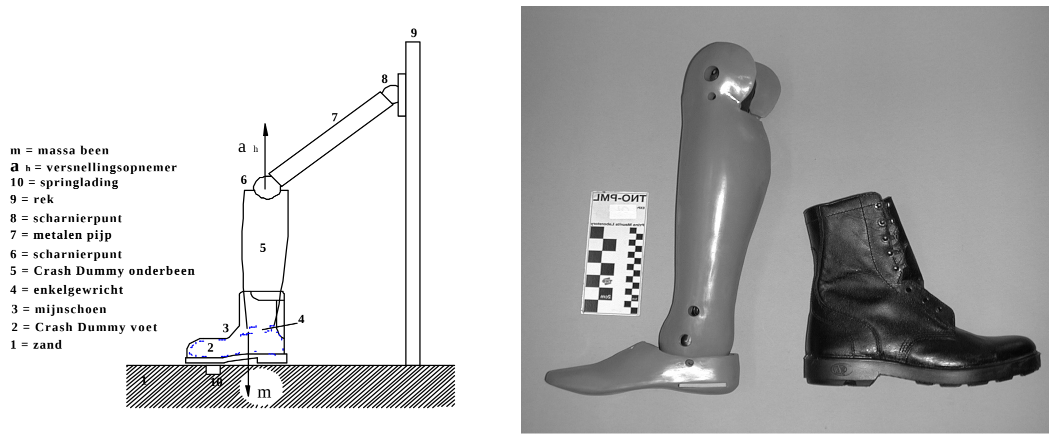

Figure 2 The Netherlands Mechanical Leg (Courtesy TNO PML, Netherlands)

<u>DRDC Mechanical Leg</u>

The DRDC mechanical leg (ML) (Coffey et al., 1999) is another example, which is currently in use as a screening tool. This mechanical leg (Figure 3) is constructed of metallic and polymeric materials. The primary structural member is an aluminum tube; with a cast urethane calf and foot to allow a conventional boot to be attached. Instrumentation includes accelerometers at the ankle and strain gauges on the aluminum shaft. The leg can be mounted to a vertical shock absorber, allowing the measurement of momentum transfer to the leg by the explosive.

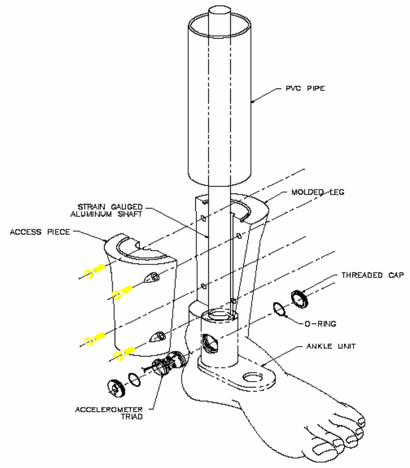

Figure 3 The DRDC Mechanical Leg (Courtesy DRDC, Canada)

Frangible test devices

The term *frangible* implies that the leg model is an approximate representation of the human leg, in terms of geometry and material properties, and includes an explicit representation of bone fracture and tissue disruption. In general, these models are expected to incur damage similar in nature to a human leg under the same test conditions. As such, these models may be evaluated using autopsy-based procedures along with various measurements from accelerometers, load cells, strain gauges and high-speed imaging. Several leg models of this type are currently available, utilizing both biological and synthetic materials to represent those of the human leg.

Artificial Leg

In 1998, Germany (Dosquet, 2000) developed a simple artificial leg using a hardwood stick, 20 mm in diameter, to represent the leg bones. The muscle tissue was represented with a similar density light concrete material. Both components were attached to a steel pelvis simulator and the leg response was captured using high-speed imaging and acceleration measurements. A diagram of the leg is shown below in Figure 4.

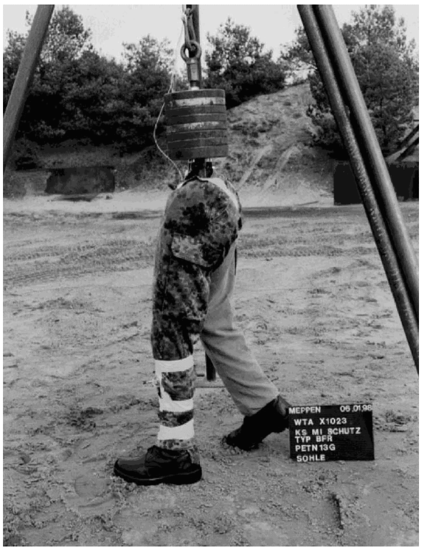

Figure 4 Artificial Leg (Courtesy WTD 91, Germany)

Red Deer Lower Limb Model

A physical model of the human leg was developed by DSTL in the UK using the hind tibia of a Red Deer (Figure 5). The primary motivation for this approach was the similarity in dimension between the Red Deer and human tibia. In addition, the mechanical properties of the bones were expected to be similar to those of human bones. The model incorporated the tibia, talus, calcaneous and metatarsal bones of the deer. Soft tissue was simulated with gelatine cast around the bones with dimensions representative of a human lower leg. Instrumentation included accelerometers mounted on the tibial plateau. Evaluation of a given protection concept was accomplished by means of a post-test examination to identify soft tissue disruption and bone fracture.

Figure 5 Red Deer Lower Limb Model (Courtesy of DSTL, United Kingdom)

Frangible Surrogate Leg (FSL)

DSTO in Australia (Krstic, 2000) have developed a frangible leg with geometry corresponding to the 50th percentile Australian male. The geometry for the bones and tissue of this leg were created by making moulds from a cadaver with dimensions corresponding to a 50th percentile male. The current version of this leg (Mk IV FSL) is constructed with representations of the bones in the human leg, as well as the tendons and soft tissues.

The FSL includes all of the major bones, which are cast with a synthetic material. The bones are then assembled (Figure 6) with adhesive and simulated tendon materials. The resulting structure is then placed in a larger mould corresponding to the outer shape of the human leg, and gelatine is cast around the structure to simulate the soft tissues (Figure 7).

Figure 6 Frangible Surrogate Leg – bone structure (Pictures courtesy of DSTO, Australia)

Figure 7 Frangible Surrogate Leg (Pictures courtesy of DSTO, Australia)

The FSL has undergone several iterations (Krstic 1999, Krstic 2000) and numerous experimental tests with various protection/threat combinations (Bergeron et al. 2002). Standard instrumentation includes strain gauges, although both load cells and accelerometers have been used with this leg. The expected trauma to the leg may be evaluated using an autopsy-based approach to identify bone fractures and mechanical tissue damage.

<u>Simplified Lower Leg (SLL)</u>

A simplified, frangible representation of the human lower leg was developed by DRDC in Canada (Bourget et al., 2000) for the purpose of evaluating landmine protection. This model consisted of a simple central bone structure to represent the tibia/fibula, talus and calcaneous (Figure 8). The bone structure is surrounded by a concentric volume of gelatine to represent the soft tissues. It should be noted that only the lower leg was considered by the model, as this is area of interest for blast mine injuries.

Figure 8 Simplified Lower Leg (Courtesy of DRDC, Canada and DGA, France)

Instrumentation included strain gauges on the bone, as well as high-speed video and x-ray imaging to record the response of the leg. This leg has been used in both Canada and France for experimental testing of protective footwear.

<u>Surrogate Complex Lower Leg (CLL)</u>

The design of the Canadian CLL (Williams et al. 2002) evolved from experience with the SLL (above). The design philosophy of the CLL was to create a synthetic surrogate leg, which could be evaluated using typical medical autopsy procedures, to identify the extent and severity of injuries expected in a human leg. Key to the development of this leg was the selection of appropriate synthetic materials to represent the hard and soft tissues of the human lower leg. These polymeric materials were selected based on high-rate and quasi-static material properties including failure strength (Cronin, 2002). The geometry was designed based on the Visible Human Database (National Library of Medicine), corresponding to the lower leg of a human male. Care was taken to represent the geometry, while maintaining simplicity to reduce cost and increase consistency between legs. In particular, the foot and ankle complex was designed to be representative of human geometry incorporating a talus and calcaneous. As with the SLL, the tibia/fibula were represented with a single bone of appropriate cross-sectional area and strength. Although instrumentation was incorporated in early versions, the current CLL is assessed with an autopsy (Williams, 2002).

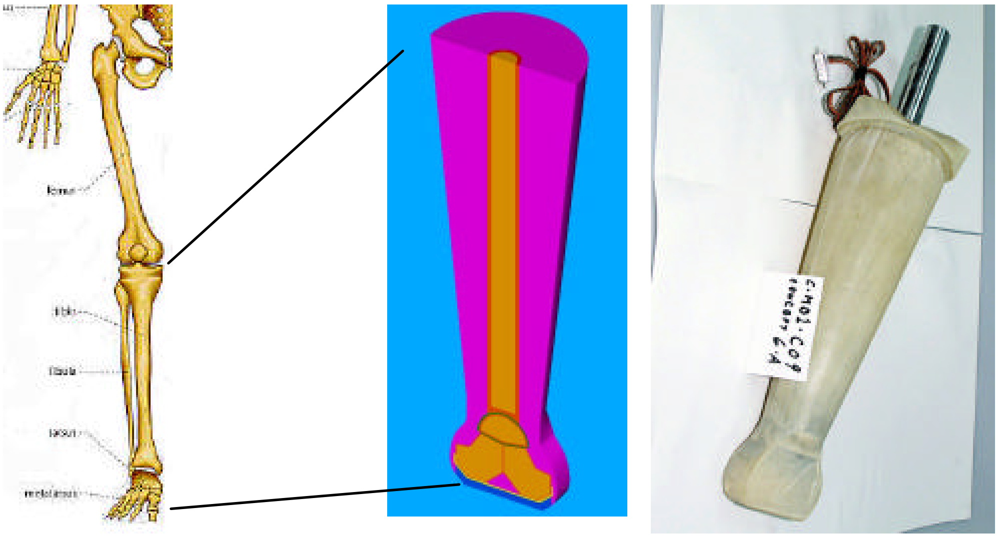

Figure 9 Surrogate Complex Lower Leg (Courtesy of DRDC, Canada)

Biological (cadaver) test devices

Biological models have been used successfully to test AP blast mine protective footwear. Such devices include whole body cadavers and isolated human lower extremities. The obvious advantage of these models is the representative geometry of the leg, and the ability to perform realistic autopsies to assess the damage to the leg. In general, the material properties of these biological models are excellent representations of the materials in a living human, with the possibility of reduced mechanical properties in the bone and tissue due to the age of the donor subject or pre-existing diseases.

Isolated human lower limb model

Researchers in the United Kingdom (Holland and Chaloner, 2000) investigated various protection concepts using amputated human lower limbs. The limbs were a mixture of above and below-knee amputations due to peripheral vascular disease. The primary benefit of this approach was that the material properties of the bone and tissue had not degraded significantly due to age, as well as the benefits of ease of handling relative to full body cadavers. The limbs were mounted in a test fixture at or near the knee joint for testing. Trauma was evaluated by means of post-test autopsies on the limbs.

Full body human cadaver body model

A significant number of full body human cadaver tests have been carried out in the United States (Lower Extremity Assessment Program, 1999 and 2000). Cadavers are typically received for testing in the 'fresh frozen' condition. They are then thawed, instrumented and tested within an appropriate time to maintain the mechanical properties of the various tissues. Instrumentation on many of the tests has included strain gauges in the vicinity of the knee, as well as at the ankle, and a load cell located in the tibia (Figure 10). However, the benefit to this approach is the ability to assess mechanical injury to the leg through an autopsy.

It is generally accepted that this is the best model to validate landmine protection, albeit with some potential constraints including availability, ethical constraints, and the ability to test with these models.

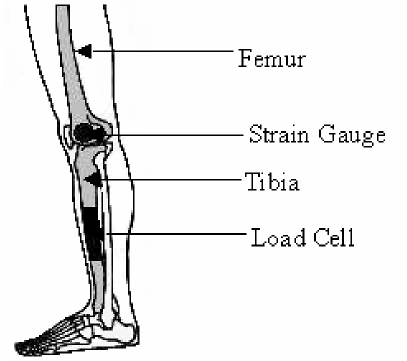

Figure 10 Instrumentation for the full body human cadaver model (Courtesy of US Army, United States)

Numerical modelling

The assessment of landmine protective footwear requires a detailed understanding of close proximity mine blast, as well as the response of complex structures to blast loading. Although experimental testing is essential for the development and verification of protective footwear, the development of new protection concepts based solely on experimental testing can be very costly. In addition, it is difficult to measure the detailed response of the footwear and leg during a blast event. Thus, numerical modelling provides a strong contribution to these development tasks by increasing the understanding of the physics of the problem.

Numerical modelling to analyze the response of the human leg to blast mines is a rapidly evolving technique. In particular, coupled Arbitrary Lagrange Eulerian – Lagrangian or Eulerian-Lagrangian analysis allows for the modelling of a detonating landmine (Magnan and Rondot, 2003) and the resulting interaction with deformable structures, such as the human leg (Cronin et al. 2000). At present, this technique has been used to successfully predict the response of a surrogate leg to a landmine blast (Motuz et al. 2003). An example of this approach is shown below in Figure 11.

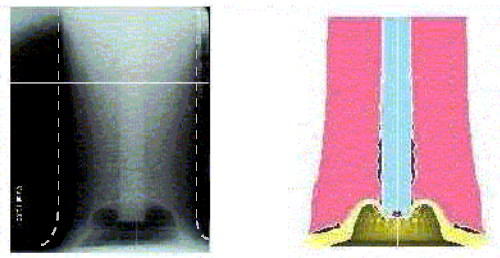

Figure 11 High-speed x-ray and numerical model of a surrogate leg subjected to a landmine blast

The ultimate goal of numerical modelling approaches is to provide a tool for the assessment of protection and prediction of trauma to the human leg. This is a rapidly evolving field, and it is expected that increasing computer power and developments in material modelling will lead to more complex models of the leg, and increased accuracy in injury prediction.

Discussion

The primary goal of testing to evaluate protection against blast mines is to predict the resulting trauma (if any) to the human leg for a given threat/protection combination. This includes mechanical damage as well as physiological damage. In reality, the various models available allow for this assessment to varying degrees, depending on the nature and complexity of the approach. Also of significance is the ability for a particular test method to accurately assess various levels of insult to the human leg. For example, increasing the explosive charge size should result in increased loading, and possibly increased injury, for a given level of protection. The ability of a test device to identify even small changes in the threat is important for a scientific ranking of various protection/threat combinations.

The evaluation of trauma, corresponding to the performance of a given protection, is of utmost importance and is specific to the type of leg model used. In all cases, various high-rate measurement techniques have been considered including strain gauges, accelerometers and load cells. These devices are essential for mechanical legs, as they provide the only means of performance evaluation. In terms of frangible and biological models, experience has shown that it can be very difficult to obtain reproducible data from these devices, and in many cases it is hard to interpret the results due to the possible failure (crushing) of various components in these models when subject to blast loading. Strain gauges have been found useful for the purposes of monitoring the arrival time of stress waves in bones. Similarly, accelerometers have commonly been used to measure the consistency between subsequent tests for a given model. Many researchers have found high-speed film and video to be of limited use due to obscuring after the initial detonation of the landmine. In contrast, high-speed x-ray has proven to be very useful to capture short-term deformation of the protection and the leg model.

As indicated above, a mechanical leg is desirable for screening as it is cost effective and requires minimal setup relative to the other models. In addition, mechanical legs provide relatively repeatable results. One of the primary drawbacks to these mechanical devices is the lack of frangibility. For example, a human leg may fail or crush under the extreme loading of a landmine blast, allowing the footwear to deform in a particular fashion. Mechanical legs do not respond in a similar fashion and might lead to a different level of apparent performance for a given protection/threat combination. It can be conjectured that a protection/threat combination which does not lead to significant injury or damage in the human leg can be assessed using a non-frangible leg. In any case, this technique is relatively straightforward to implement and can be used to screen potential protection concepts, using a particular evaluation parameter such as acceleration of the test device.

The philosophy behind the use of frangible legs is that a more accurate representation of the human leg, including material failure, will lead to a more accurate evaluation of the protection. In addition, the available control on material properties and geometry allows for high repeatability between tests. One issue with all of the current frangible models is the use of gelatine as a tissue simulant. This material has been used widely by the ballistics community to simulate penetrating trauma in human tissue for many years, and is likely a reasonable choice for blast injury. The difficulty with this material lies in the short shelf-life and corresponding refrigeration requirements, which can complicate test procedures.

Biological models are accepted as the best representation of the living human leg, both in terms of geometry, construction and material properties. However there are some limitations to this approach, one being that many countries cannot actively participate in this type of testing. Further, there are variations in geometry and material properties between different cadavers leading to difficulties in repeatability between tests. The cadaver age and medical history may also not be representative of the anticipated population, leading to additional variability in the test results.

It must be emphasized that all of the above test devices lack the very important physiological data (e.g. nerve damage and viability of soft tissue) necessary to evaluate the true extent of the trauma, with the biological (cadaver) test device being most accurate. Each approach relies on the correlation between mechanical damage or response and the expected trauma in the human leg to evaluate blast mine protection.

Conclusions

The development of a test methodology for protective footwear against blast mines includes the definition of a threat and a means of evaluating a particular form of protection. To date, users have considered representative charges of C-4/PE-4 explosive as surrogate landmines for experimental consistency, complemented by ease of handling and availability. Means of evaluation typically involve various human leg models with associated injury estimates. The available models can be defined in three categories: screening (mechanical legs), proofing (frangible legs) and validation (human cadavers).

The selection and implementation of a particular test methodology requires careful consideration, and is guided primarily by the motivation for the testing. Simple, re-usable mechanical models are appropriate for economically screening various types of protection, but may not provide a detailed assessment of injury or a realistic backing for protection concepts. Increased accuracy of assessment requires more detailed models, such as frangible legs, which have the added benefit of experimental consistency due to control of material properties. It is generally accepted that human cadaver models provide the best means for validation of landmine protection, albeit with some limitations regarding experimental consistency and, more importantly, ethical constraints that may preclude its usage in many countries.

Numerical modelling is an emerging technique that is expected to play a strong role in the evaluation and development of existing and new landmine protection. Advanced computational methods are leading to improved numerical models and accuracy in the prediction of trauma to the human leg.

At present, the proposed models do not allow for the assessment of physiological parameters such as nerve damage. This type of injury must be inferred from observable mechanical damage and relevant test measurements.

The testing of blast mine protection has progressed significantly under the mandate of the HFM-089/TG-024. It is expected that this increased understanding will provide a suite of well defined test methods and evaluation criteria for the testing community.

Acknowledgements

The author thankfully acknowledges the funding from his sponsoring organisations including Materials and Manufacturing Ontario, Defence R&D Canada, Med-Eng Systems Inc. and the Canadian Centre for Mine Action Technologies.

Contributions and insight from the TG-024 members are gratefully acknowledged.

References

Coffey, C.G., Torrance, K., Lonson, D., Markov, A.B., "Design, construction and commissioning of a surrogate human leg test facility, Amtech Report TR9775.2701, rev. 1, November 1999.

Bergeron, D., Walker, R. and Coffey, C.,,"Detonation of 100-Gram Anti-Personnel Mine Surrogate Charges in Sand", Report number SR 668, Defence Research Establishment Suffield, Canada, 1998.

Bergeron, D. and Tremblay, J., "Canadian research to characterize mine blast output", MABS 16, Oxford, UK, 11-15 September 2000.

Bergeron, D.M., Anderson, I.B., Coley, G.G., Rountree, M.S., Fall, R.W., Harris, R.M., 'Assessment of Lower Leg Injury from Land Mine Blast – Phase 2 – Test results using an Improved Frangible Surrogate Lower Leg and Comparison with Cadaver Test Data', Defence R&D Canada – Suffield, Technical Report 2002-004, 2002.

Bourget, D., Pageau, G., Williams, K.V., and Cronin, D.S., "AP Mine Blast Effects on Surrogate Lower Leg", MABS 16, Oxford, UK, 11-15 September 2000.

Coupland, R.M., War Wounds of Limbs – Surgical Management, Butterworth-Heinemann Oxford 1993.

Cronin, D.S., *Salisbury, C., Worswick, M.J., Pick, R.J., Williams, K.V. and Bourget, D., "Appropriate Material Selection for Surrogate Leg Models Subjected to Blast Loading", Explomet 2000, Albuquerque, New Mexico, July 2000.

Cronin, D.S., "Complex Lower Leg – Design, Development, Testing", HFM-TG024 Meeting, September 11-13 2002, St. Petersburg, Florida (USA).

Dosquet, F., "AP Mine Protective Footwear Assessment Procedures" HFM-TG024 meeting, May 13, 2002, Porton Down (UK).

Dobratz, B.M., LLNL Explosives Handbook, Properties of chemical explosives and explosive simulants, University of California, Lawrence Livermore National Laboratory, Rept. VCRL-52997, 1981.

Gregory, R.T., Gould, R.J., Peclet, M., Wagner, J.S., Gilbert, D.A., Wheeler, J.R., Synder, S.O., Gayle, R.G., Schwab, W., The mangled extremity syndrome (MES): A severity grading system for multisystem injury of the extremity, J. Trauma, 25(12), 1147 – 1150, 1985.

Griffin, L.V., Harris, R.M., Hayda, R.A., Rountree, M.S., A Model of Lower Extremity Morbidity Subjected to Antipersonnel landmine Blast, Proceedings of the 2001 UXO Conference, New Orleans, USA, April 2001.

Harris, R., Griffin, L., Hayda, R., Rountree, M.S., Bryant, R., Rossiter, N., and Mannion, S., "The effects of antipersonnel blast mines on the lower extremity", IRCOBI Conference, Sitges, Spain, September 1999.

Harris, R., Mannion, S. and Rountree, S., "The Effects of Antipersonnel Blast Mines on the Lower Extremity", HFM-ET-007 Meeting, Brussels Belgium, 22 February 2000.

Holland, S. and Chaloner, E., "The Use Of The Tabre System In Vehicle Protection Trials", HFM-ET-007 Meeting, Brussels Belgium, 22 February 2000.

Kinney, G.F., Explosive Shocks in Air, Macmillan Company, New York, 1962.

Krstic, A.R., Australian Patent No: PQ1424 entitled ‘A Surrogate’ July 1999.

Krstic, A.R., Australian Patent No: AUPQ8943 entitled ‘A Surrogate’ July 2000.

“Lower Extremity Assessment Program (LEAP)”, TECOM Project No. 8-EI-495-BPF-001, Report No. ATC-8199 (Volume I), USAIR, August 1999.

“Lower Extremity Assessment Program (LEAP 99-2)”, TECOM Project No. 8-EI-495-BPF-001, Report No. ATC-8199 (Volume II), USAIR, August 2000.

Magnan, P. and Rondot, F., “Mapping of Air Overpressure around Surrogate AP Blast Mines”, Minutes of the AVT097/HFM102 RSM Meeting, Koblenz, Germany, 19-23 May 2003.

Motuz, J., Salisbury C., Cronin D.S., Worswick M.J., and Williams K.V., "Material Characterization and Numerical Modeling for Landmine Protection Concepts", Shock and Vibration Journal, SAV 10(3), June 2003.

National Library of Medicine, “Visible Human Project”, 8600 Rockville Pike
Bethesda, MD 20894.

Roberts, I., “MOD DCTA Antimine Boot”, HFM-ET-007 Meeting, Brussels, Belgium, 22 February 2000.

van Bree, J.L.M.J., “HFM/ET007 Position paper”, HFM-ET-007 Meeting , Brussels Belgium, 22 February 2000.

Williams, K., Bourget, D., Cronin, D.S., Salisbury, C. and Bergeron, D., “Surrogate Lower Leg”, U.S. Provisional Patent, August 2002.

Williams, K., “Complex Lower Leg – Experimental Testing”, HFM-TG024 Meeting, September 11-13 2002, St. Petersburg, Florida (USA).