Development of a Test Methodology to Evaluate Mine Protective Footwear

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1. Introduction

There are an estimated 110 million landmines in place around the world, and there are further threats to military personnel in combat situations. Individuals involved in antipersonnel demining efforts face a large threat of traumatic injury especially to their lower extremities. Landmine injuries may be very severe, often resulting in amputation or death, but protective equipment worn during these missions must be a balance between safety and mobility. However, there is no current objective test methodology to evaluate the effectiveness of protective footwear against antipersonnel landmines.

One of the two main goals of this study was to develop an injury risk function for assessing the risk of mine injuries using mechanical force data and to use this risk function to develop a test methodology for assessing boot performance using a dummy surrogate limb. A second equally important goal was to evaluate commercial, state of the art lower extremity AP mine protective footwear for use in mine clearance in current operations.

In this study, a total of 42 surrogate landmine tests were conducted at the U.S. Army Aberdeen Testing Center with both cadaveric lower extremities (20 tests) and a mechanical dummy lower extremity (22 tests). The simulated mine charges used in this test series were made from C-4 explosive packed into standardized plastic containers. The mines used in this study varied in size

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from 50 grams to 200 grams of C-4. This variation in charge size allowed the investigation of a large range of possible mine threats. The mines were placed directly under the heel for the mechanical limb and under the calcaneus of the cadaveric limbs. Previous tests [Leap-1999] have shown that this position may represent a worst-case scenario for explosive shock loading to the tibia

This study developed a three level grading procedure for boot damage. Three levels were used, BD1-BD3, that ranged from minor external boot damage (BD1) to severe damage with major boot containment breach (BD3). These boot damage levels were found to be well correlated with injuries produced in the cadaveric limbs. Further, an injury risk function for risk of lower extremity injury was developed using a survival analysis with an assumed logistic distribution. This injury risk function, based on measured axial compressive load in the cadaver tests, has a 50% risk of AFIS-S>2 injury for 8600 N axial load. This value is comparable to values derived for lower extremity injuries in automobile crashes after accounting for the large difference in strain rates.

A dichotomous objective test methodology was developed for the deliberate mine clearance mission. The first stage of this process is an evaluation of the boot damage results. The boot damage results suggested that boots fail if damage is greater than BD1. The second stage of the process is an evaluation of the axial load for boots with BD1 using the injury risk function developed in this study. If the injury risk is greater than 50% the boot fails, if less than 50%, the boot passes. In drawing a correlation between the axial loads of the dummy limb and the cadaver limbs it appears there is a nonlinear correlation between the average force peak of the dummy tests and the average force peak of the biological tests. However, owing to the limited number of tests conducted for each charge size and boot type, more tests are needed before a conclusive relationship can be established.

2. Test Method

The positioning fixture for the LEAP II test series was assembled from a combination of several fixtures that have been used in earlier tests of lower extremity landmine protection. The resulting test fixture consisted of a surrogate leg and foot attached to a translating crosshead. The translating crosshead was mounted onto a pedestal fixture that allowed the surrogate leg and foot to be positioned onto a surrogate landmine. The surrogate limb and crosshead were designed by the Canadian Defense Research Establishments at Valcartier and Suffield respectively. The base in which the surrogate landmine was placed was a U.S. (ATC) design. The test fixture is shown in Figure 1.

Four commercial off the shelf and the standard Army overboot were used in the testing. These boot types are termed boot A, boot B, boot E, boot ME1, and boot ME2. There were 13 dummy tests and 20 cadaver tests using these boot types. Three of the boots, A, B, and E, represent boots with different sole thickness, while the ME1 and ME2 boots consist of a rectangular platform mounted on top of four short legs extending from each corner.

Thirteen dummy tests using the surrogate foot and test fixture discussed above were performed using the 50 gram and the 75 gram charge sizes, and twenty cadaver tests were performed using 25 gram, 50 gram, 75 gram, 100 gram, and 200 gram charge sizes.

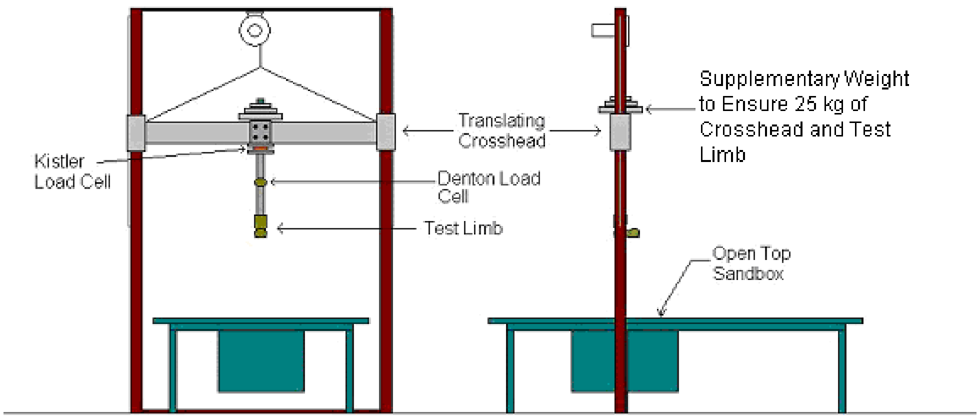

Figure 1. Overview of the Test Fixture

3. Results

Boot Damage

After testing, each boot was examined to assess the amount of damage it sustained. The damage was categorized into 3 levels, with category 1 (BD1) being the least extensive and category 3 (BD3) being the most extensive. A listing of these levels with a description of each is shown in Table 1. A plot of the average damage assessment versus boot type and charge weight can be seen in Figure 2. Boot damage generally increased with charge weight, and generally decreased with boot standoff from the mine.

For both cadaver and dummy tests, the ME1 and ME2 boots were the only boot types to sustain only BD1 damage with the higher mine charge sizes (75g, 100g, 200g). Though the boot damage level remained constant, the injury level in the test limbs increased with the peak force and charge size.

Boot Damage Levels	Description of Damage Levels
BD1	Minor damage to boot (i.e. portion of sole blown off; insole destruction)
BD2	Structural damage to boot (i.e. minor blast penetration into foot compartment of boot)
BD3	Breach (i.e. massive blast penetration into foot compartment of boot)

Table 1. Boot Damage Level and Description

Injury Scoring

The injuries to the cadaveric specimens were quantified using standard injury scales including AFIS-S [Levine-1995]. The AFIS-S is a numerical rating system that ranges from 0 (no injury) to 6 (currently untreatable). The AFIS-S evaluates injuries based on an expected recovery outcome and therefore is able to accurately predict the sequelae from lower extremity injuries.

These injury scores may be plotted against the boot damage assessment for the cadaveric extremities tested as shown in Figure 3. If the boot was severely damaged, the result was invariably a traumatic amputation of the foot or a severe (AFIS-S=6) injury. This suggests that boot damage level may be used as a preliminary assessment of the blast performance for a given boot. However, it is clear that this is not sufficient as there are several severe injuries obtained in testing in which the boot damage level is 1 (BD1). This means that a secondary assessment, based on sensor data including force, must be used to provide a full assessment of the blast performance of a given boot.

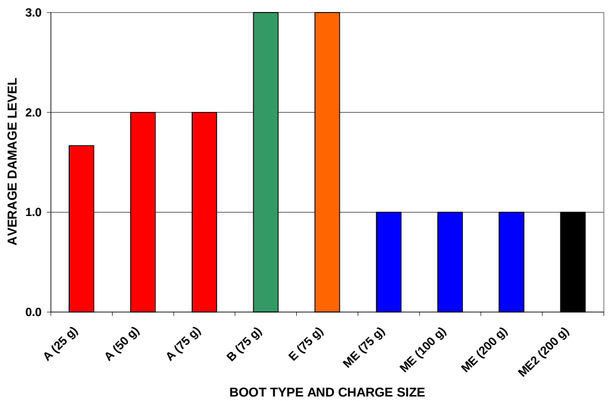

Figure 2. Average Damage Level versus Boot Type and Charge Weight for Cadaveric Tests

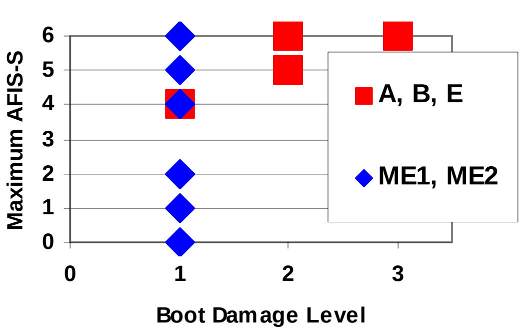

Figure 3. Maximum AFIS-S vs. Boot Damage Level

Injury Risk Function

In comparing the boot damage to the level of injury sustained to the lower extremity, it can be suggested that the boot damage assessment can be used as a preliminary evaluation of the blast performance for a given boot. However, a secondary assessment based on sensor data must be used in order to provide a thorough appraisal of a boot's blast performance. Using the injury assessment values discussed previously, injury risk functions may be derived based on axial force values. These risk functions are derived using a binary survival analysis [c.f. Funk-2000]. Assuming a logistic distribution, the risk functions were calculated using a parametric survival analysis.

For the creation of the risk function relative to the AFIS-S injury scores, it is assumed that the injury results occur at the peak axial compressive force, and are therefore considered uncensored data. The justification of this is that once injury occurs the force path is destroyed. The one exception is that tibia lip fractures are not necessarily force limiting injuries. Therefore tibia lip fractures, along with the non-injury results, are considered to be right-censored data.

Four injury risk functions were derived using AFIS-S for boot damage levels of BD1 and BD2. All results exclude boot damage levels of BD3 because the result of these tests was major destruction of the lower limbs. This level of damage destroys the load paths giving the limb a different character. AFIS-S levels greater than 2 were selected to represent a significant injury. The injury risk for injury with AFIS-S > 2 and boot damage levels BD1 and BD2 is shown in Figure 4 with the injury and non-injury tests. The axial force level to produce a 50% risk of injury is approximately 8600 N with relatively tight 95% confidence intervals of 7500 N to 9700 N at 50% injury risk.

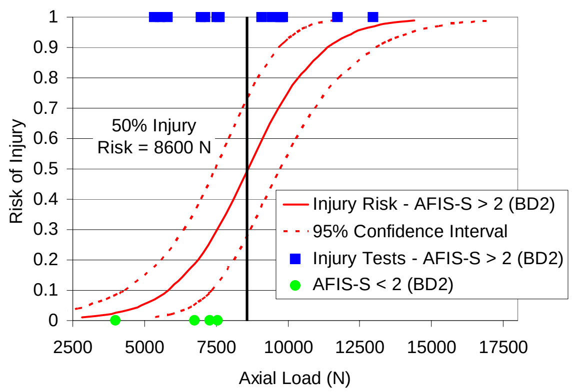

Figure 4. Injury Risk Function Based on AFIS-S>2 Injury for Cadaver Tests with BD1 and BD2

Cadaver to Dummy Transfer Function

To derive a cadaver to dummy transfer function, peak axial compressive loads were used. The ratio of peaks for matched tests is shown in Figure 5. It is clear that the dummy is substantially stiffer than the cadaver and that there may be a nonlinear relationship between the dummy to cadaver peak axial load ratio for different boot types. Further, there are only three matched conditions using seven total dummy tests to develop a transfer function. So, there is not enough data to establish a full relationship. However, a preliminary transfer function could be constructed using a nonlinear force relationship between dummy and cadaver.

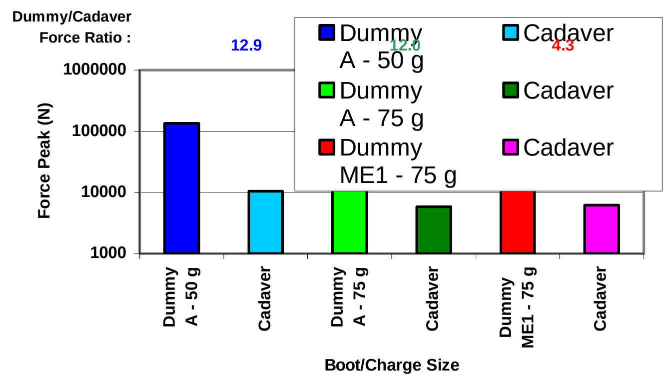

Figure 5. Dummy/Cadaver Transfer Function

4. Conclusions

Elements of a Boot Test Methodology

Essential elements of an objective test methodology are a repeatable, robust, reusable surrogate that has been validated by an injury model. The injury model should have the same characteristics as the situation envisioned by the test. These elements are satisfied here with some recommended changes to the test methodology. The essential elements of the test methodology are reported below:

Test Environment

A standard test environment has been developed in collaboration with U.S., Canadian, and Australian researchers [c.f. Bass-2001, Bergeron-2001]. The mine blast tests use a medium grain dry sand to minimize the effect of the potential variation in soil. The tests are performed using a test box that is at least 61 cm on a side. For consistent results, tests are performed using a standardized mine form [c.f. Bass-2001, Bergeron-2001] filled with a standardized explosive (C-4). The standardized mine form is available in several sizes for use as an antipersonnel mine, 25 g, 50 g, 75 g, 100 g, 150 g, and 200 g.

Data Acquisition

Mine blasts are generally high rate events with substantial power in their frequency spectra; therefore, data acquisition parameters have been standardized. Data should be sampled at better than 200 kHz with anti-alias filtering to at least 40 kHz to attenuate spurious high frequency content in the sensors. Special care must also be taken to isolate sensors from the blast [Bass-2001].

Test Fixture

The dummy foot/leg and fixture generally performed well. However, there was some loosening of internal parts of the fixture after multiple tests. This can be mitigated using thread adhesive. Care must also be taken to wipe the bearing rods after each test to avoid sand entry to the bearings causing fixture sticking. If significant kinematics is expected in the blast event, a compliant element may be introduced to produce a more realistic response. The dummy foot, constructed of Adiprene polymer, saw some damage in the ankle body component used in testing at ATC. From radiological images, no damage was seen in a similar foot used in testing at the Canadian Defense Research Establishment – Suffield, even though the feet were tested at similar force levels. There are, however, slight differences in design, and the current DRES design should be adopted to strengthen the foot design.

Injuries

Injuries seen in the cadaveric testing are similar to axial loading injuries seen in automobile crashes. Injury risk curves have been developed in this study that are similar to lower extremity axial load injury risk curves as developed by Funk [c.f. Funk-2000].

For the deliberate demining mission, the injury level selected for a pass-fail criterion should be a closed injury, no greater than AIS-2 or AFIS-S-3. This selection should limit injuries so that, for the tested mine size, the risk of injuries that would result in an amputation would be low.

Test Procedure

The objective test methodology should follow a dichotomous procedure. The key justification for this technique is that, above a certain level of damage, the blast wave loading destroys load-bearing surfaces and thus decreases load values seen in load sensors. The goal of this procedure is to provide a standard injury risk for the objective test methodology that provides a functional lower extremity for a given mine size. The two stages of this procedure are:

Stage 1. The boot should be tested on the dummy device for a given mine and should be analyzed for damage. If the boot has boot damage level BD2 or BD3, the boot fails the procedure. If the boot damage has BD1, the boot should proceed to the second stage.
Stage 2. The axial load from the dummy should be evaluated using the injury risk function for AFIS-S<3 injury transferred to the dummy developed in this study. If the injury risk is greater than 50%, the boot fails; if less than 50%, the boot passes.
It is recommended that at least five tests per test condition be performed for a boot to pass. For a boot to fail, one test with BD2 or BD3 should be sufficient.

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