Loading Rate and Torsional Moments Predict Pilon Fractures for Antipersonnel Blast Mine Loading

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ABSTRACT

Our objectives were to use force and strain data, radiographic and visual documentation, medical assessment to determine meaningful predictors of lower extremity morbidity, using a medically relevant antipersonnel landmine model. We wanted to determine if antimine protective footwear provide a measurable reduction in injury. Finally, we wanted to obtain empirical data for the development of injury threshold criteria, which can be used to enhance the predictive power of blast-rig data by establishing a correlation between human injury and force-based data. Twenty fresh frozen full human cadavers were used, and six groups of footwear representing a spectrum of protection were evaluated. Three mine threat levels were used. The cadaver lower extremities were instrumented with a uniaxial or multiaxial load cell placed in the proximal tibia. Strain gages applied to the distal tibia and calcaneus. The heel with protective measure was placed directly over the land mine. High-speed video (13,500 frames per second) and cineradiograpy was used to visually document the blast event. Load and strain data were sampled 100 kHz. Two orthopaedic traumatologists performed clinical dissection the lower extremity to determine the medical outcome which ranged from traumatic amputation to a closed, minimally displaced fracture of the talus and calcaneus. We found statistically significant predictors of pilon fractures were axial peak force, axial loading rate, anterior shearing force, and torsional peak moments. While some footwear offered modest protection against the smallest mines, no footwear we evaluated were able to reliably reduce injury to a level that would not require extensive hospitalization and rehabilitation.

Keywords : bones, cadavers, injury probability, legs

THE PROLIFERATION AND USE of landmines as weapons in modern conflict has led to a global problem of epidemic proportions. By United Nations (UN) estimates, there may be as many as 100 million uncleared mines worldwide (Korver, 1993). Authorities estimate that landmines kill 800 people per month and injure an additional 1200, accounting for at least 24,000 new victims per year (Croll, 1998). Many organizations believe that these injury statistics are a conservative estimate, and do not represent the total number of casualties per year, since many victims may never reach the medical treatment facilities from which these statistics were compiled (Gray, 1997).

The presence of landmines may impede the economic and social development of countries recovering from conflict, as the safe use of farmland and water resources can be denied to residents. When faced with the possibility of starvation, families often resort to cultivating mined areas, sometimes resulting in detonation of a buried landmine. Handicapped victims are less able to support themselves in agrarian countries, and represent an economic burden to their families and communities; where average family incomes may be less than $250 per year. The International Committee of the Red Cross (ICRC) estimates the cost of providing a 10-year-old child with a lifetime of basic prosthetic limbs to be $3125 (Garachon, 1993). Consequently, many needy people never obtain the required treatment to become productive members of society.

The UN and other non-governmental organizations (NGOs) have initiated de-mining programs in response to this landmine epidemic. Antipersonnel landmines can be classed in five categories, but the most prevalent type is the blast mine, which uses the detonation of an explosive charge as an injury causing mechanism (Taylor, 1999). The blast mine can be either surface laid or buried and is activated by pressure when stepped on. The process of locating and removing mines poses a significant injury risk to individuals involved. Injuries from landmines can affect the lower extremities, and various types of protective footwear have been developed in an attempt to reduce the incidence of lower extremity morbidity. Current protective strategies include single and multiple boot configurations, which often include selective use of energy absorption materials, such as metallic honeycomb and may increase standoff from the blast.

Evaluation of the effectiveness of footwear is usually conducted using blast-rigs, such as shown in Figure 1. However, the correlation between blast-rig data (e.g. forces, accelerations), and injury is not well defined since so-called safe levels of force related parameters are not known. A review of the literature demonstrates there are few systematic evaluations of anti-mine footwear to determine protective capability from a medical perspective.

Figure 1 - Example of an antimine footwear blast-rig.

The purpose of our study was to determine the protective capabilities of commercially available anti-mine protective footwear from a medical perspective. Our objectives were to use the force and strain data, medical outcome, radiographic and visual documentation to determine meaningful predictors of lower extremity morbidity. We wanted to determine if the protective footwear provided any improvement in medical outcome. Finally, we wanted to obtain empirical data for the development of injury threshold criteria, which can be used to enhance the predictive power of blast-rig data by establishing a correlation between human injury and force-based data.

METHODS AND MATERIALS

The US Army Institute of Surgical Research's Institute Review Board, in accordance with all Federal, State, and Local regulations, approved the protocol used for these tests. In addition, the US Army Medical Research and Materiel Command Human Subject Review Board reviewed the protocol, considering all ethical issues. All Federal, State, Local and Regulatory Commission rules were observed in the purchase, disclosure, transportation, and storage of the cadavers.

Twenty fresh-frozen full body human cadavers were obtained from a Willed-Body Program (average age 75 $\pm$ 17 years, range 37 – 96 years, and mass 73 $\pm$ 14.1 Kg). The cadavers were stored in a freezer maintained at -4 °C. Five days prior to testing, the cadavers were thawed in a refrigeration unit maintained at 7.2 °C.

Pretest specimen evaluation was conducted by a complete study of the lower extremity and consisted of plain radiographs using anterior/posterior (AP) views of the pelvis, and AP and lateral views of the femur, knee, tibia, ankle, and foot. Computed axial tomography (CT) of the complete lower extremity was conducted using 5 mm slices (Picker PQ 5000). A radiologist and orthopaedic traumatologist examined the x-ray and CT data, fully documenting any pre-existing pathology such as a fracture.

The coordinate system reference is the load cell in the proximal tibia. The x-axis is positive anteriorly, the y-axis is positive to the right, and the z-axis is positive distally along the long axis of the bone (SAE standard coordinates). All forces and moments follow the right-handed system convention, with the exception of the z-force, which was inverted such that a positive z-force is compressive.

Forces and moments were measured with either a uniaxial load cell (Model 9332A, Kistler Instrument Corporation, Amherst, NY) or six-axis load cell (Denton Instrument Corporation). A ten-centimeter segment of the diaphysis was removed from the proximal tibia ten centimeters below the tubercle using a surgical saw (Stryker, Santa Clara, CA). The load cell was physically attached to two stainless steel cups potted into place at the proximal and distal ends of the tibial resection using polymethyl-methacrylate (Palicos R, Richards, Memphis, TN). Each cup was further secured by using two stainless steel Kirschner wires (2 mm diameter) protruding through the cup, cement, and bone (transverse to the long axis) in orthogonal directions.

Surface strains were measured on the medial malleolus and lateral calcaneus using two percent strain gages (Micro Measurements, Raleigh, NC). The bone surface was exposed by careful dissection of tissues and stripping of the periosteum, followed by degreasing with acetone, and the gages were bonded using a fibrin glue. The exposure was surgically closed and gage continuity was verified by direct measurement of resistance.

Force and strain data were acquired at 100 KHz, and digitally filtered at 10 KHz using a 4th Order Butterworth filter (MATLAB Release 11). We obtained the peak value of force and strain as well as the time to peak value from the data using computational algorithms (MATLAB Release 11). For the force components, we calculated the components of impulse. For the axial (z) component, we calculated the loading rate, impulse at peak force, and pulse width. We defined the loading rate as the linear portion of the impulsive load and used 20 percent and 80 percent of the maximum load as baseline values of load rate calculation. The load rate and pulse width definitions are shown in Figure 2. The impulse, defined as the area under the force time history, was obtained by numerically integrating using a trapezoidal rule. The pulse width is defined as the duration of time over which the majority of the impulsive load was applied, as shown in Figure 2. If the data were noisy, parameters were determinate manually using the Signal Processing tool (sptool) in MATLAB.

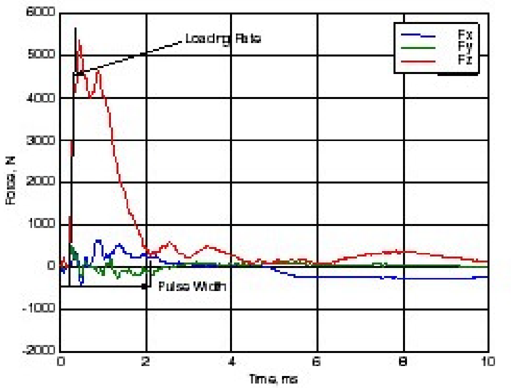


Figure 2 - Loading rate and pulse width definitions.

Three mine threat levels were used based on explosive weight: the M14 mine, represented the smallest type of blast mines (< 50 grams TNT), the PMA-2 represented mid-sized mine (50 – 150 grams of TNT) and the PMN represented large mines (>200 grams of TNT). Six types of footwear, listed in Table 1, were evaluated, representing a spectrum of protection.

Table 1 - Protective footwear that were evaluated.

Boot Type	Manufacturer	Protective Measure	Code
Sandal	Improvised	Unprotected	Sandal
Combat Boot	Ro-Search	Standard Military	CB
BFR 40V	BFR	Single, Antimine	BFR
Blast Boot	Wellco®	Single, Antimine	BB
Over Boot	Wellco®	Multiple, Antimine	OB
Spider Boot	Med-Eng®	Multiple, Antimine	Med-Eng

Tests were conducted in a steel biohazard containment shelter (3 × 3 × 3 m). The mine was buried in dry sand contained in a steel box (0.46 × 0.61 × 0.61 m) located in the center of the biohazard shelter floor. The top of the mine was flush with the ground directly under the heel. The cadaver was suspended upright in a harness that used a modified thoracic lumbosacral orthosis (TLSO) to stabilize the hips. The test limb was fitted with the footwear of interest and the knee of was braced in a fully extended position (one-legged stance). The contralateral (non-test) limb was suspended in a fully flexed position and further protected from by the blast by Kevlar soft body armor.

Classification of the landmine injury and determination of the amputation level in a cadaveric model required the development of a trauma scoring system. Clinical limb salvage criteria, such as the Mangled Extremity Severity Score (MESS), require evaluation of neurovascular function which is not present in cadavers (Dirschl, 1996; Durham, 1996). The blast landmine injury is characterized by significant disruption of hard and soft tissue structures of the foot and ankle with gross contamination (Jacobs, 1991; Korver, 1993). Therefore, a scoring system to predict the level of salvage or amputation based on soft tissue findings was developed for use in a cadaveric model termed the mine trauma score (MTS), summarized in Table 2, and was developed based on the clinical experience of orthopaedic traumatologists experienced with the clinical management of landmine victims. The MTS assesses injury severity is based on the condition of the hard and soft tissues, both of which are necessary to determine if an amputation would be the likely outcome as well as the probable level of amputation.

The post-test medical evaluation began with plain radiographs and CT, in accordance with the pre-test protocol. Documented injuries were compared to the pre-test condition. Clinical dissection of the lower extremity was performed by one of two board-certified orthopaedic traumatologists to provide a detailed medical assessment of injury to bone, joint, soft-tissues, and neurovascular structures. The dissection was filmed and reviewed by two other traumatologists who assigned a MTS based on their judgment. The evaluator was blinded to the mine and footwear used for the particular test as well as the assessments of the other clinicians. The reported score was arrived by consensus of the three clinicians after all dissections were reported.

Table 2 - The mine trauma scoring system.

Medical Assessment	MTS	Injury Condition
No major injury	0	
Salvageable Limb	1	Closed
	1A	Open contained
	1B	Open contaminated
Trans-tibial amputation	2	Closed
	2A	Open contained
	2B	Open contaminated
Trans-tibial/Trans-femoral	3	
Trans-Femoral	4	

The cineradiography data were obtained using an eight channel, multi-anode flashed x-ray head. The x-ray source (450 KeV) was linked to an ultra-high speed digital framing camera. The system is able to acquire eight images at 1 million frames per second. The digital x-ray images in this study were obtained at 4000 fps, allowing for approximately 2 milliseconds of radiographic documentation.

Statistical analyses of data were performed using ANOVA, simple correlation, bivariate correlation, and binary logistic regression models (Minitab V12.2). Results were considered significant when $p<0.05$.

RESULTS

The detailed medical assessments revealed five types of fractures to the hind foot and ankle which were characteristic of lower extremity bone injury due to blast mine activation. These were comminuted (multi-fragmented) calcaneal, cuboid, navicular, talus, and pilon fractures (intra-articular fractures of the distal tibia). Direct correlation of biomechanical data to the MTS tended to reveal inverse relationships to measured data. In other words, these comparisons suggest that lessening the severity of mine injury can be obtained by transmitting higher loads, greater impulses, strains, etc at higher rates measured by the load cell. The inverse relationships are partially demonstrated in Table 3 and Figure 3 where the average peak force decreases with injury severity.

Table 3 – Axial (Z) force data for the blastboot/overboot combination.

Shot	Protective Measure	Mine	MTS	Peak Force (N)	Time to Peak Force (ms)	Loading Rate (KN-ms)	Pulse Width (ms)	Impulse (N-s)	Time to Peak Impulse (ms)	Impulse @ Peak Force
1-7	BB/OB	M14	1	9356.07	0.81	42.35		33.90	16.13	2.10
6-2	BB/OB	M14	2	8794.71	0.95	21.30	9.50	37.69	27.64	1.51
8-2	BB/OB	M14	2A	7895.02	0.80	26.10	21.00	30.34	25.02	1.00
10-2	BB/OB	M14	1	12623.74	0.91	80.00	14.80	42.98	14.86	2.60
14-2	BB/OB	PMN	2B	15876.41	0.72	116.80	5.00	15.00	5.00	0.66
15-2	BB/OB	PMA2	3	11741.56	0.58	43.17	9.00	17.97	7.73	0.70
17-2	BB/OB	PMA2	2B	10650.56	0.68	62.29	7.00	34.54	28.89	1.86

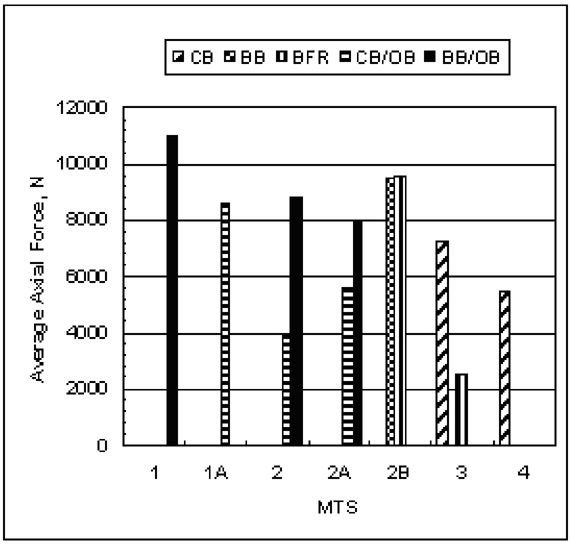


Figure 3 - Average of peak axial (Z) force for each MTS obtained with the M14 antipersonnel mine.

On the other hand, we observed a positive trend of increasing number of bone fractures with MTS (Figure 4). We also found the comminuted calcaneus fracture is associated with MTS 1 for mine blast under the heel. There is also a clear positive correlation between the condition of the boot and the MTS as shown in Figure 5. The positive trends can collectively be used to assess injury and possible medical outcome.

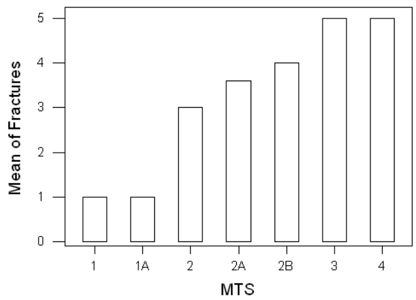
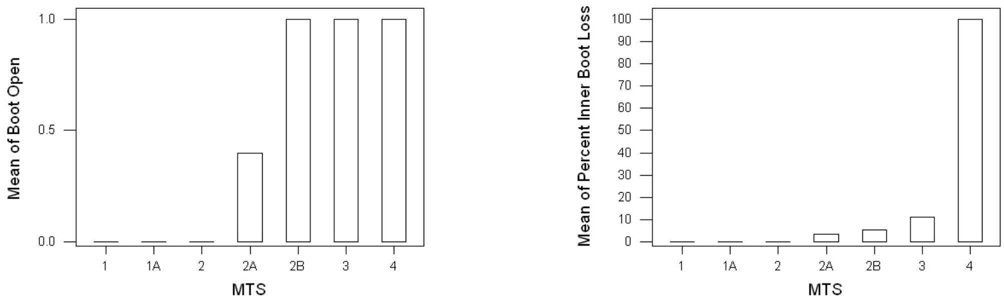


Figure 4 - The average number of characteristic fractures to the hind foot and ankle as related to MTS.



(a) (b)

Figure 5 - Condition of the inner boot as a function of MTS. (a) The average number of occurrences of open boots. (b) Percentage of boot loss.

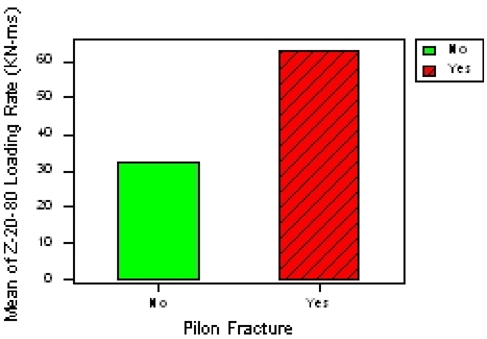
Force Data

Based on our observation that fracture patterns correlate with injury severity, we focused our attention on the pilon fracture since we are directly measuring forces in the tibia. Figure 6 shows that statistically significant predictors of pilon fractures are axial loading rate, axial impulse, axial peak force, and charge weight. We did not find any other force component related parameters that independently predicts pilon fractures. The inverse relationship between the axial impulse and pilon fracture is different, but related to the fact that the when the tibia was not fractured, it resulted in a longer exposure to high forces, whereas the other parameters correlate positively with the pilon fracture. We observed that the rate at which x force (AP) is applied also appears to be important in predicting pilon fractures (Figure 6c).

Table 4 shows the number of pilon fractures per number of replicate tests for all footwear and mine levels. Figure 7 shows the axial peak force data as a function of mine weight for all tests. While the trend for peak force appears to be positively correlated to mine explosive weight; the definitive mine trauma score cannot be ascertained by direct comparison as shown in Figure 3. The large variance in peak force for the 240 gram mine has two major source: (1) several mines did not fully detonate (evidenced by fragments of un-detonated explosive in post-blast examination) or (2) the blast was so severe that the lower limb was traumatically amputated at mid-tibia level, resulting in low axial force transmission.

Table 4 - Frequency of pilon fractures for all tests and protective measures.

	Protective Measure								
	Least →							*Most*	
Mine	*Sandal*	*CB*	*BFR*	*BB*	*CB/OB*	*BB/OB*	*BFR/OB*	*Canadian*	*Total*
M14	1/1	5/5	1/2	1/1	0/5	2/5	*	*	10/19
PMA2	*	*	*	*	1/1	4/5	*	1/1	6/7
PMN	1/1	1/1	*	*	0/1	3/3	2/2	2/3	9/11



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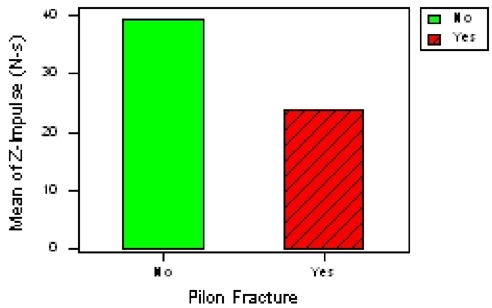

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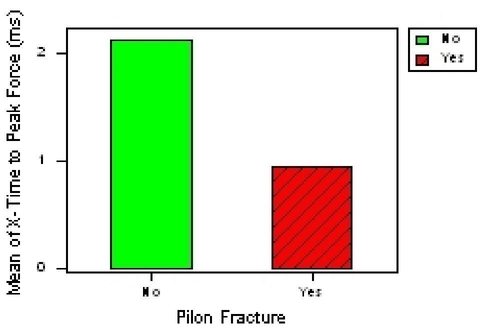
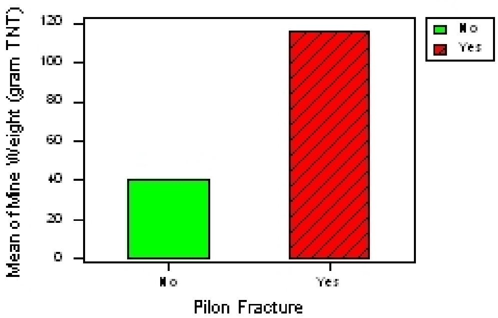




(c) (d)

Figure 6 - Statistically significant predictors of pilon fractures. (a) Axial (Z) loading rate (p=0.027). (b) Axial (Z) Impulse (p = 0.01). (c) Time to peak X (AP) force (p=0.05). (d) Explosive charge (p=0.022).

Figure 8 shows a survival plot for pilon fractures involving the variables axial loading rate, time to peak force, and axial impulse. For this plot, it was assumed that the axial impulse had a constant value of 30 N-s, which was the average value of axial impulse for our data.

Estimated Risk of Pilon Fracture $$p = \frac{1}{1 + \exp\left(-8.39 - 0.078R + 0.073W + 5.2 \times 10^{-5} Fz\right)} \quad (1)$$

In Equation 1, R is the axial loading rate (KN/ms), W is the subject weight (lbs), and Fz is the peak Z force (N).

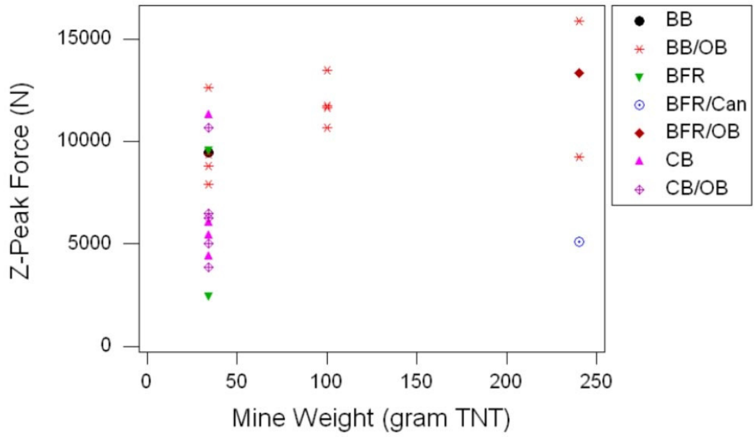


Figure 7 - Peak axial (Z) force measured for all tests as a function of mine explosive weight.

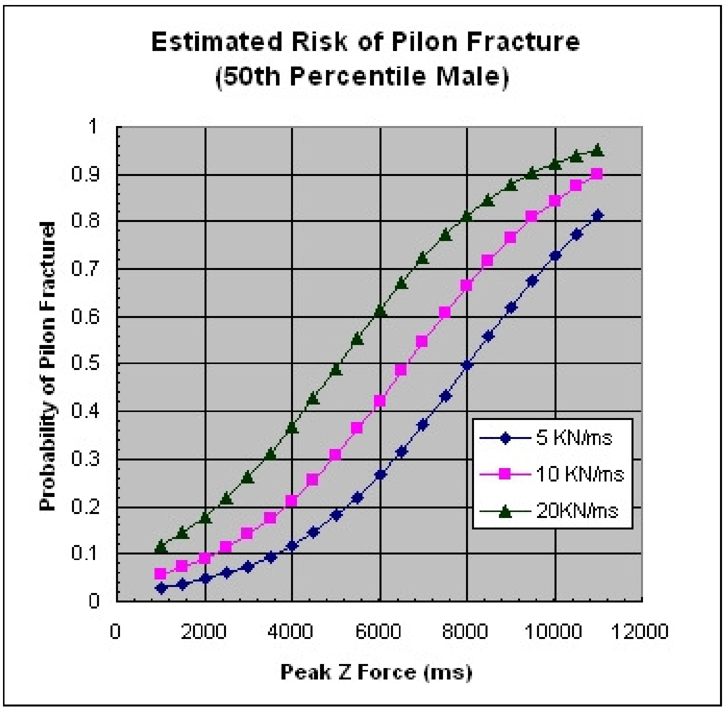


Figure 8 – Estimated risk of pilon fracture for Peak Z-force at various loading rates.

Logistic regression analyses further revealed that specimen weight and age do not predict pilon fractures ($p = 0.67$). We also found no trend between any statistically significant predictors, such as axial loading rate and age or weight.

Moment Data

The moment data show the same inverse trend as the force data. Figure 9, shows the statistically significant predictors of pilon fractures. In addition to the axial loading rate, a maximum torsion of 30 N-m appears to be critical since we found no incidence of fractures below this value as seen in Figure 9b and 9c. For all the cases shown in Figure 9, the direction of the torsion was internal rotation.

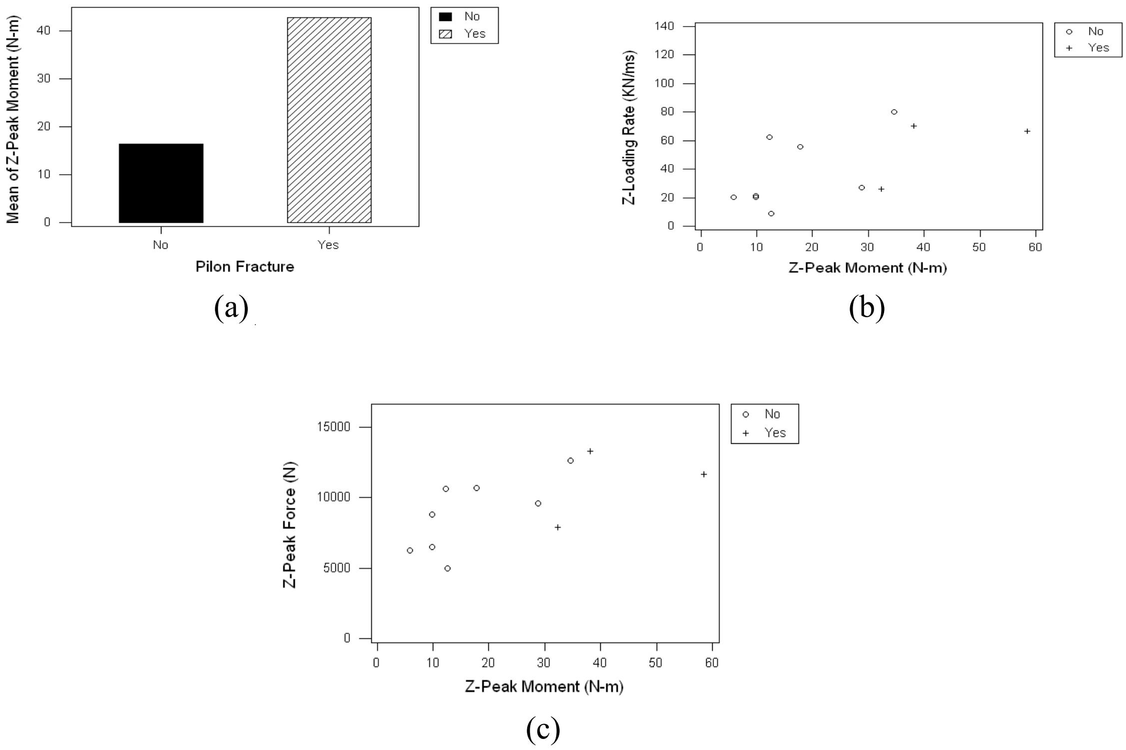


Figure 9 - Statistically significant moment predictors of pilon fractures. (a) Peak torsional moment (p = 0.006). (b) Incidence of pilon fractures related to loading rate and torsional loading. (c) Incidence of pilon fractures related to axial peak force and peak torsional moment.

The results of a survival analysis for torsion and pilon fractures are shown in figure 10. This plot uses a Weibull distribution for the data. The goodness of fit tests suggest that this model is adequate.

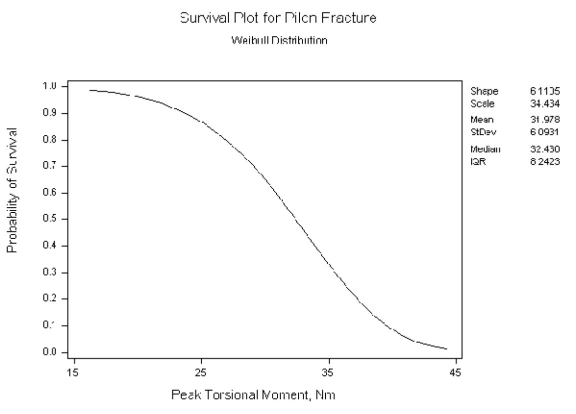
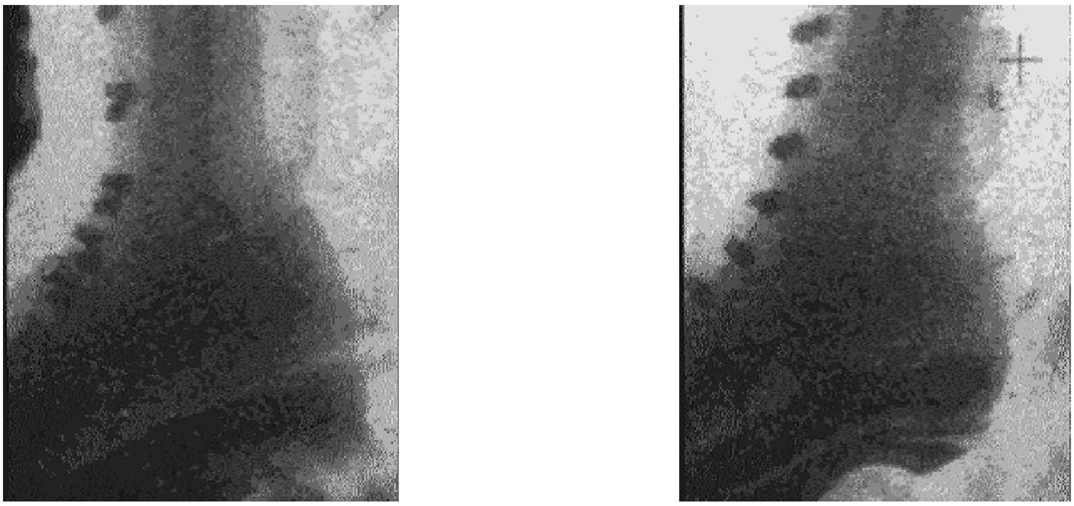


Fig 10 – Survival plot for pilon fractures as a function of torsional loading.

Cineradiography

The cineradiography data did not have bony resolution of medical quality due to scattering. While it was not possible to resolve the details of the internal structural failure processes, the external boot deformation and foot positions were recorded, providing an appreciation of the damage extent.

Cine x-ray data for shots 8-2 (BB/OB-M14) and 10-2 (BB/OB-M14) are shown in Figure 11. The major differences appear to be the extensive deformation at the boot heel in Figure 10b. In both cases, the inner boot was not compromised; however, the examination for shot 8-2 (Figure 11a) revealed a highly comminuted, open *mangled* extremity, with minimal contamination. The medical assessment was a trans-tibial amputation, with delayed primary closure (MTS 2A). The clinical examination for shot 10-2 (Figure 11b) was a closed comminuted fracture of the calcaneus with a minimally displaced fracture of the talar body. This may have been surgically treated by open reduction internal fixation and possible subtalar fusion, with no amputation (MTS 1).



(a) (b)

Figure 11 – Cineradiograpy images of two different tests involving BB/OB and M14 mine at 2.0 ms for (a) shot 8-2, MTS = 2A, and (b) shot 10-2, MTS = 1A.

DISCUSSION

We found several interesting observations regarding lower extremity fracture patterns, especially the pilon fracture. Due to the very large forces generated during the blast mine activation, we observed a large number of pilon fractures (see Table 4). Since we measured forces on the tibia, we have been able to determine possible contributing factors to pilon fractures as well as a tentative injury criterion.

While we documented many different types of fractures to the lower extremity, we found five that seem to be characteristic of the landmine foot. Appendix 1 is a listing of the five characteristic fractures and test-specific data. The MTS, however, cannot be defined easily in terms of the number or type of fractures to the lower extremity. There is undoubtedly some difficulty and uncertainty in determining the level of tissue viability in a cadaver model; however the level of contamination can be determined with a modest level of effort. With the exception of gross tissue disruption, none of the clinically significant tests for tissue viability can be applied –

thus exempting the clinical limb salvage criteria, such as AIS, ISS, MESS etc. However, injuries to the hard tissues, such as a talar body, calcaneal, or pilon fracture are sustained in other high-energy situations, and therefore, the fracture data should be broadly applicable.

The inverse relationship between force and MTS as seen in Figure 3 is related to the failure of the foot/ankle complex. Peak forces were measured in the proximal tibia, and since the foot and ankle are generally obliterated with the higher MTS, forces in the proximal tibia were less. This also accounts for why the axial impulse is greater with a lower MTS.

We conducted a binary logistic regression to develop a risk function for pilon fractures as seen in figure 8. Rate is the strongest predictor from a statistical perspective, while weight and peak force (Fz) are weaker. While not significant, we have included the weight as an estimator of bone strength, yet due to the sensitivity of the equation to weight, we are not confident of the equation with respect to extrapolation to other weight. We cannot estimate the affect of sex, since we only had two females and one was not instrumented. Our results suggest a greater risk for pilon fracture with increasing age (not shown) and higher rate of loading.

Our observations appear consistent with other high-energy phenomena, such as motor vehicle crash. Safe limits of loading to axial prevent injury to the tibia are on the order of 7500 N (Funk *et al.*,2001; Sherwood *et al.,* 1999; Yoganandan, *et al* 1997). Assuming that 10 KN/ms is representative of automobile crashes (based on a strain rate of 2 ε/s, elastic modulus of bone 20 GPa, and that the tibial cross-sectional area is about 240 mm^2) we estimate that 6800 N represents a 50 percent risk of pilon fracture for a 50th percentile male (Figure 8). This suggests that our blast data have a broader application, and may be useful to researchers developing foot and ankle injury criterion.

Our data did not show any influence of age and weight on the incidence of fracture to the lower extremity. It is well documented that the strength of bone is strongly related to bone mineral density, which correlates well with age, sex, and weight (Carter & Hayes, 1977; Les, *et al.,*1994). Age, sex, and weight are primarily not factors in our study because 18 of the 20 specimens were male, and would be classified as a 50th percentile. Therefore, the specimens were of similar strength, which was our part of our experimental design; since most individuals involved in humanitarian de-mining efforts are 50th percentile male.

Our data are consistent with the literature that bone can tolerated higher magnitudes of axial loads if the rate at which they are applied rapidly, and the duration is short. This is primarily because bone is a viscoelastic material (Carter & Hayes, 1977, Fondrk, 1988, Lakes, 1979, Rimnac, 1993). Carter and Hayes (1977) found that the presence of the marrow significantly affects energy absorption at strain rates of 10.0 ε/sec, which may account for why the bone can tolerate higher loads at higher strain rates. The landmine blast is a characteristically short duration event, and we found no significant correlation between pulse duration and injury. The upper limit to the axial load is about 11000 N, but this is value is strongly dependent on the loading rate. The axial impulse is a strong predictor of pilon fractures;

however the inverse relationship makes data assessment difficult, except as a threshold for judging limb survival when considering other factors.

Our data predict that the torsional moment is the strongest estimator of the pilon fracture (p=0.006) (Figure 9). This is interesting, but since this finding is based on a limited sample of usable torsional data (N = 11), and with only three instances where pilon fractures did not occur, definitive conclusions of torsional limits cannot be drawn based solely on our data.

As seen in Figure 10, we estimate that 32 ± 6 Nm represents a 50 percent risk of fracture. These data compare favorably to those of previous studies. Begeman et al (1994) reported that torsional loads to the foot and ankle tended to produce malleolar fractures under torsional loads of approximately 34 Nm. Markolf *et al* (1989) reported an average of 45 Nm for injury in a cadaveric model. Yet none of the literature we have found suggest that pure torsional loading can produce a pilon fracture. While we cannot definitively determine the mechanism of injury from our work, it seems reasonable to conclude that the coupling of a high axial force with modest torsion presents a significant risk of a severe injury to the foot and ankle complex.

While it is generally accepted that the high energy pilon fracture is dominated by axial loading, for which parameters such as axial loading rate should be important, torsional loads are known to cause pilon fractures as documented in the medical literature (Borner, 1982, Mast *et al.* 1988, Mandracchia *et al.*, 1999, Neuman *el al.*, 2000, Ruwe *et al.* 1993, Teeny *et al*., 1993). However, pilon fractures caused primarily by torsional loading tend to be associated with low-energy incidents, such as sports accidents.

With the complex geometry of the foot and ankle, axial loading may generate torsional moments naturally in a physiologic context; however, it is highly unlikely that there would be a so-called pure states of stress, such as found in laboratory tests of materials. To test if axial loading produced torsional loads, we performed a simple correlation analysis between the time-to-peak torsional moment and time-to-peak axial force. The results were not significant ($R^2 = 0.04$ and $p = 0.57$). This suggests that the torsion and axial loads are not causally related, and therefore, we believe that a distinct coupling between torsion and axial loading may exist to cause the pilon fracture. However, when a pilon fracture did occur, its time to peak value was very close to that of the time to peak Fz. From our observations, we feel more work should be performed to define the specific relationship between axial load, torsion and pilon fractures.

Single boot configurations.

We evaluated three single boot footwear: the US Army combat boot, the Wellco blast protective combat boot, and the BFR 40 (Singapore) blast protective combat boot. Our data provides no evidence that any single blast boot is more effective in protecting the foot than the standard US Army combat boot. This is shown in Figure 3 where all of the tests involving single boot resulted in a MTS of 2B or higher for the smallest mine we evaluated (M14).

Multiple boot configurations.

The remaining anti-mine strategies we evaluated involved multiple boots. The primary blast overboot we evaluated was the Wellco overboot. We tested it with the standard US Army combat boot (CB/OB), the Wellco blast protective boot (BB/OB), and the Singapore boot (BFR/OB). The use of a multiple boot combination may potentially reduce the injury for the smallest landmine we evaluated. We found no instances of an MTS greater than 2A for the M14 mine when the overboot is used. We also found that there are no statistically significant differences between the type of inner boot used. For the M14 mine, the medical outcome would be the same if an individual was wearing a combat boot or blast boot under the Wellco overboot. *This is not to suggest that the individual would not be a casualty nor suffer an amputation, as we found no instances where at least one major bone of the foot was not fractured when subjected to a mine detonation with an boot/overboot combination*.

When we evaluated the protective capability of the boot/overboot strategy against the larger AP blast mines (PMA2 and PMN), we determined that the Wellco overboot is not effective in preventing amputation. Considering that the largest numbers of mines worldwide are in the mid to large class (Taylor, 1999), we conclude that the Wellco overboot combined with any footwear is an inadequate protective measure for personnel involved in de-mining operations.

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APPENDIX A: Data from all tests along with injuries to foot/ankle complex.

Table A-1: Test data and injury to foot/ankle complex. Data are coded as follows: Ca = calcaneus, Cu = cuboid, T = talus, N = navicular, P = pilon. The code one indicates a communuted fx, while the value 0 indicates either no fx or a minimally displaced fx.

Test #	Age (yrs)	Mass (kg)	Limb	Boot	Mine	MTS	Hard Tissue Injury					Tibia Fz (N)	Time to Tibia Fz (ms)	Load-Rate (KN-ms)	Z-Impulse (N-s)	Z-Peak Moment (N-m)
							Ca	Cu	T	N	P					
1-1	92		L	CB	M14	3	1	1	1	1	1					
1-2	82		L	CB	M14	3	1	1	1	1	1	4377.309	0.49	22.60	16.30	
1-3	82		R	CB/OB	M14	2A	1	1	1	1	0	3862.6	1.83	12.84	21.65	
1-4	86		L	CB	M14	3	1	1	1	1	1	6061.8	0.59	87.23	17.59	
1-5	86		R	BB	M14	2B	1	1	1	1	1	9478.1	0.50	54.70	10.64	
1-6	81		L	CB	M14	3	1	1	1	1	1	11274.1	0.48	130.70	24.21	
1-7	81		R	BB/OB	M14	1	1	0	0	0	0	9356.1	0.81	42.35	33.90	
2-1	96	65.0	L	CB	M14	4	1	1	1	1	1	5429.0	0.42	42.34	9.39	
2-2	96	65.0	R	CB	PMN	3	1	1	1	1	1					
2-3	80	91.0	L	BB/OB	M14	2A	1	1	0	0	1					
2-4	80	91.0	R	CB/OB	M14	1A	1	0	0	0	0	6496.8	0.73	20.28	49.48	9.80
2-5	94	66.7	L	CB/OB	M14	2A	1	1	0	1	0	6264.8	1.86	20.21	39.83	5.92
2-6	94	66.7	R	BB/OB	M14	2	1	1	0	0	0	8794.7	0.95	21.30	37.69	9.90
2-7	81	65.0	L	CB/OB	M14	2A	1	1	1	0	0	5000.8	1.93	9.03	37.18	12.60
2-8	81	65.0	R	BB/OB	M14	2A	1	1	1	0	1	7895.0	0.80	26.10	30.34	32.26
2-9	83	61.9	L	BB/OB	PMA2	2B	1	1	1	1	1					
2-10	83	72.7	L	BB/OB	M14	1	1	0	0	0	0	12623.7	0.91	49.78	42.98	34.57
2-11	83	61.9	R	CB/OB	PMN	2B	1	1	1	1	0					
2-12	83	72.7	R	CB/OB	M14	1A	1	0	0	0	0	10669.4	0.82	55.50	40.96	17.76
2-13	61	62.3	L	CB/OB	PMA2	2B	1	1	1	1	1					
2-14	61	62.3	R	BB/OB	PMN	2B	1	0	1	0	1	15876.4	0.72	116.80	15.00	
2-15	81	43.8	L	BB/OB	PMA2	3	1	1	1	1	1	11741.6	0.58	43.17	17.97	
2-16	81	43.8	R	BB/OB	PMA2	2B	1	1	1	1	1	11666.7	0.61	66.40	21.85	58.44
2-17	37	65.1	L	BB/OB	PMA2	2B	1	1	1	1	0	10650.6	0.68	62.29	34.54	12.33
2-18	37	65.1	R	BB/OB	PMA2	2B	1	1	1	0	1	13477.2	0.63	54.57	36.09	
2-19	86	84.7	L	BFR	M14	3	1	1	1	1	1	2505.1	4.68	5.21	21.27	
2-20	80	81.2	L	BFR	M14	2B	1	1	1	1	0	9606.0	0.52	27.30	54.68	28.84
2-21	86	84.8	R	CB/Can	PMN	NA	0	0	0	0	0	1594.1	0.10	29.28	5.55	
2-22	80	81.2	R	BFR/OB	PMN	2A	1	1	0	1	1	13319.0	0.75	70.04	65.76	38.11
2-23	86	84.7	R	BFR/Can	PMN	2A	1	1	0	1	1	5128.2	0.88	116.60	5.67	
2-24	71	92.5	R	BFR/OB	PMN	2B	1	1	1	1	1					
2-25	71	92.5	L	BB/OB	PMN	2B	1	1	0	0	1	9258.4	1.40	44.40	40.47	
2-26	83	71.1	L	Sandal	M14	2B	1	1	1	1	1					
2-27	83	71.1	R	Sandal	PMN	4	1	1	1	1	1					
2-28	43	62.1	L	BB/OB	PMN	3	1	1	1	1	1					
2-29	73	88.2	L	BB/Can	PMA2	2A	1	1	1	0	1					
2-30	45	50.9	L	BB/Can	PMN	2B	1	1	1	1	0					
2-31	73	88.2	R	BB/Can	PMN	1	0	0	0	0	1					