THE EFFECTS OF ANTIPERSONNEL BLAST MINES ON THE LOWER EXTREMITY

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ABSTRACT

The objectives of our study were: a) to evaluate the relative efficacy of antipersonnel mine protection offered by various de-mining footwear; b) to determine the *in-situ* forces and strains experienced by the lower extremity under blast conditions; c) to document the blast event, and d) medically evaluate the injury to the lower extremity that results from activation of a antipersonnel blast mine. Four fresh frozen full human cadavers were used, and four combinations of protective footwear were evaluated. The cadaver lower extremities were instrumented with a uniaxial load cell placed in the proximal tibia and strain gages applied to the distal femur. Each lower extremity was suspended with the boot heel placed directly over the landmine. High-speed video (13,500 frames per second) was used to capture the blast event and load and strain data were sampled 100 kHz and 50 kHz, respectively. Orthopaedic traumatologists examined the post blast lower extremities to assess the injuries, which ranged from an open, mangled lower extremity to a closed, minimally displaced fracture of the talus and calcaneal fracture. The results of this study suggest that practical mine protective measures may be feasible.

LANDMINE INJURIES have reached epidemic proportions in third-world nations, and affect both combatants and civilians. During 1980-1993, the incidence of landmine related injuries doubled, resulting in an estimated 2000 deaths or injuries per month (Rutherford 1997). By United Nations estimates, there are more than 100 million uncleared mines worldwide (Korver, 1996).

In an effort to reduce the level of trauma to the lower extremity from antipersonnel mines, attempts have been made to design protective footwear. In the early 1950's the U.S. Marine Corps developed a 6–inch sabot attachment for the combat boot, while the Army evaluated protective shanks in the 1960's. Work conducted at the US Army Natick Research, Development and Engineering Center in the 1990's has led to the development of new antimine footwear. Antimine footwear has never been evaluated to determine its protective capability from a medical perspective. The purposes of our study were: a) to evaluate the relative protection offered by various de-mining footwear; b) to determine the *in-situ* forces and strains experienced by the lower extremity under blast conditions; c) to document the blast event, and d) medically evaluate the mine injury to the lower extremity that results from activation of a blast antipersonnel mine.

METHODS AND MATERIALS

Four fresh frozen human cadavers (2 male and 2 female) were obtained from the willed body program and screened for hepatitis and HIV in conformance to our institutional review board's (IRB) approved protocol. The age and sex data for the subjects are listed in Table 1. Cadavers were kept frozen at -4 °C except for instrumentation, radiography, testing and examination phases. Prior to testing, the full lower extremity of the cadavers were screened for abnormality or pre-existing injury by standard radiography, computerized axial tomography (CAT) scan (Picker PQ 5000) and magnetic resonance imaging (MRI) (GE SIGNA 5.2).

Table 1 – Age and sex data of cadavers used in the study.

Subject	Age	Sex
1	92	F
2	82	F
3	86	M
4	81	M

Four combinations of standard military footwear (Ro-search) and anti-mine footwear (Wellco) were evaluated and are listed in Table 2. Figure 1 shows the types of footwear evaluated. Figure 1b shows a cutaway of the anti-mine footwear with the blast attenuation plate and aluminum honeycomb.

The tests were conducted according to Table 2. The first cadaver was uninstrumented in order to evaluate the injury patterns and facilitate the placement of instrumentation in subsequent tests. A uniaxial load cell (Model 9332A, Kistler Instrument Corporation, Amherst, NY) was used to measure force. A four-inch segment was removed from the proximal tibia using a surgical saw (Stryker, Santa Clara, CA). The load cell was potted into place using polymethyl methacrylate (PMMA) and further secured by drilling transversely to the bone and using 2 mm diameter stainless steel wires at the proximal and distal ends of the load cell. The load data were sampled at 100 kHz with a 10 kHz low-pass filter.

Table 2 – Blast protective measures that were evaluated

Test Code	Description
A	Standard U.S. Army Issue Combat Boot
B	Combat Boot with Blast Protective Overboot
C	Blast Protective Combat Boot
D	Blast Boot with Blast Protective Overboot

Strain gages (Measurements Group, Raleigh, N.C.) were bonded directly to the distal end of the femur on the antero-medial (A-M) and antero-lateral (A-L) regions. The strain gages used provide accurate strain measurement up to 2% strain (20000 $\mu\varepsilon$). The gages were connected to a one active arm bridge. The strain data were recorded wide band with a sampling rate of 50 kHz.

The cadavers were transported from the morgue to the test site in a refrigerated truck and remained refrigerated until the conduct of the test. Prior to the test, the subject was clothed and outfitted with the various protective measures listed in Table 3.

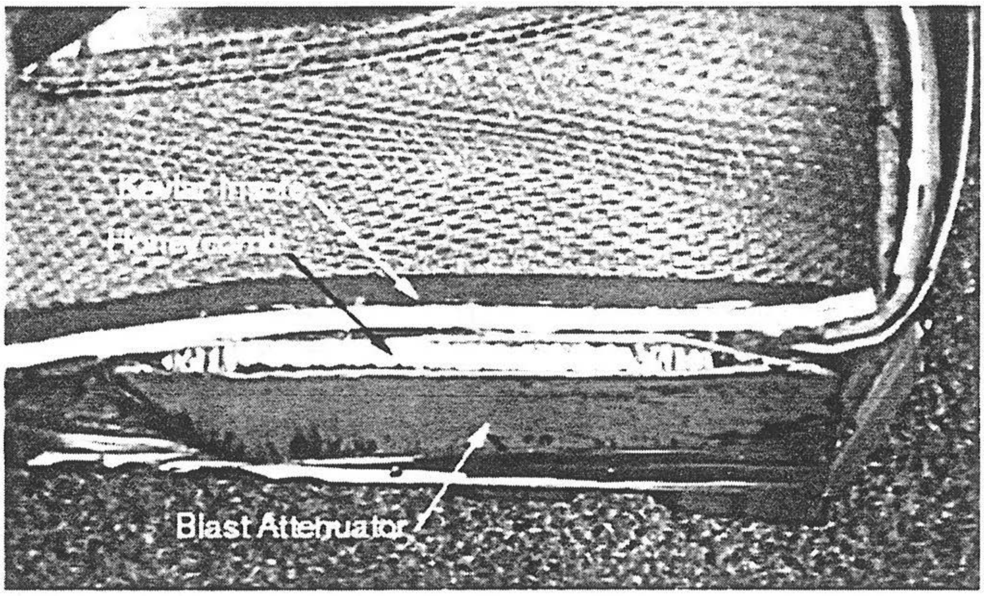
Table 3 – Order in which the tests were conducted.

Test	Subject	Foot	Footwear
1	1	L	A
2	2	L	A
3	2	R	B
4	3	L	A
5	3	R	C
6	4	L	A
7	4	R	D

The mine was deployed in a box of sand with the top of the mine flush with the ground and in contact with the boot. Fluorosceine dye was added to the sand to assess the amount of foreign debris in the soft tissue after the blast by inspection under a Woods lamp. The subject was then suspended upright in parachute hamess, the foot positioned directly over anti-personnel blast mine, simulating a single leg stance, with sufficient body weight to activate the mine. The contralateral limb was suspended away from the blast and further protected by use of Kevlar weave blast protective trousers.

The blast was triggered remotely using an electronic blasting cap. Load and strain data acquisition were triggered simultaneously with the activation of the mine. High speed video (13,500 frames per second) was used to capture the blast event.

(a)



(b)

Fig. 1 – The protective measures evaluated. (a) From left to right: blast protective overboot, standard combat boot, and blast protective combat boot. (b) A cutaway view of the blast boot. The overboot internal structure is identical.

After the blast, orthopaedic traumatologists evaluated the lower extremities by visual inspection, dissection, using standard x-ray and pre- and post-blast CT and MRI images, for limb disruptions, crushes, comminuted fractures, and other hard and soft tissue trauma, and level of limb contamination. Using these data, injuries were graded as shown in table 4.

Table 4 – Mine trauma score.

Outcome	Damage Score	Score Description
No Injury	0	--
	1	closed
Salvageable Limb	1-A	open, contained
	1-B	open, contaminated
Below Knee Amputation	2	closed
(BKA)	2-A	open, contained
	2-B	open, contaminated
Below/Above Knee Amputation	3	
Above Knee Amputation (AKA)	4	

Data for the test were analyzed using Matlab (V 5.2, The Mathworks, Inc., Natick, MA) and Minitab (V 12.1, State College, PA). Mechanical parameters considered were peak values of strain and load, and impulse defined as:

$$I = \int_0^{t_f} F dt \qquad (1)$$

where the finish time, t_f, was the instant of maximum impulse where the effects of the blast subsided or 50 ms after the mine activation, whichever came first. Other parameters evaluated were impulse at peak force, and the loading rate was defined such that the 20 percent and 80 percent values of maximum load were used to determine the linear portion of the loading curve (Crandall, 1999). Time to peak force was defined as the instant from which data acquisition began until time of peak force was observed.

RESULTS

The peak loads and strains as well as the times to peak are listed in Table 5. The first cadaver was not instrumented, and the strain data for the third test were not usable due to instrumentation problems. In Table 5, the strains are provided as the maximum value experienced. Listed in Table 6 are the values of the time to peaks referenced to the data acquisition start time, along with the impulse found by numerically integrating the force time data.

The strain data for test 5 are shown in Figure 2. It is interesting to note the sign difference of the strains, indicating that some bending in the anterior-posterior plane occurs. Shown in Figure 3 are the force time traces for standard combat boot (tests 2, 4 and 6). For these measures, the event is substantially complete after 2 milliseconds. The 0.2 millisecond delay common to all the data results from the time to ignition from the point at which the signal to detonate was sent. It is interesting to note the similarity in the blast pulse for each of the subjects, as far as the time to the peak events and shapes, although the magnitudes of the impulses are different. The data shown in Figure 4 are more remarkable in that the event is much longer for protective measures B and D showing that the impulse occurs over a longer time than in the case of the non-protected boot of Figure 1. Both of these measures are for a boot/overboot combination.

Table 5 – Force and strain data for all the experiments

Test	Maximum Force, N	Maximum Strain, $\mu\varepsilon$ (A-M)	Maximum Strain, $\mu\varepsilon$ (A-L)	Minimum Strain, $\mu\varepsilon$ (A-M)	Minimum Strain, $\mu\varepsilon$ (A-L)
2	4398	1901	1902	-1878[a]	-1877[a]
3	3894	-[b]	-[b]	-[b]	-[b]
4	6101	4328	1473	-1565	-1842
5	10013	1059	1657	-1381	-1612
6	11003	1842	921	-1658	-1473
7	9561	3315	10130	-1427	-1289

[a] Strain data clipped
[b] Data not

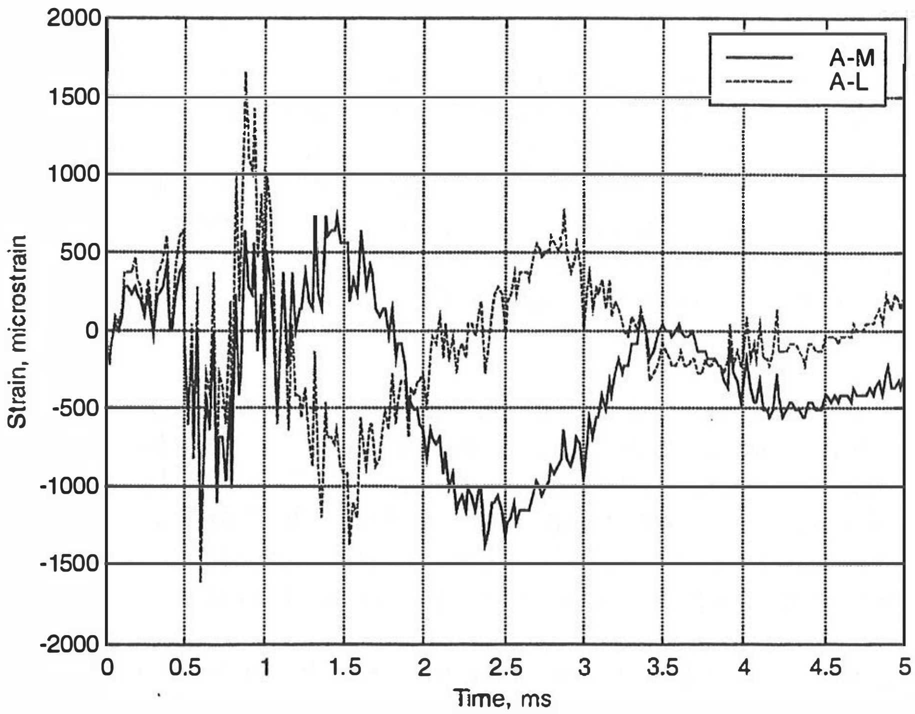


Fig. 2 – Strain data for test 5.

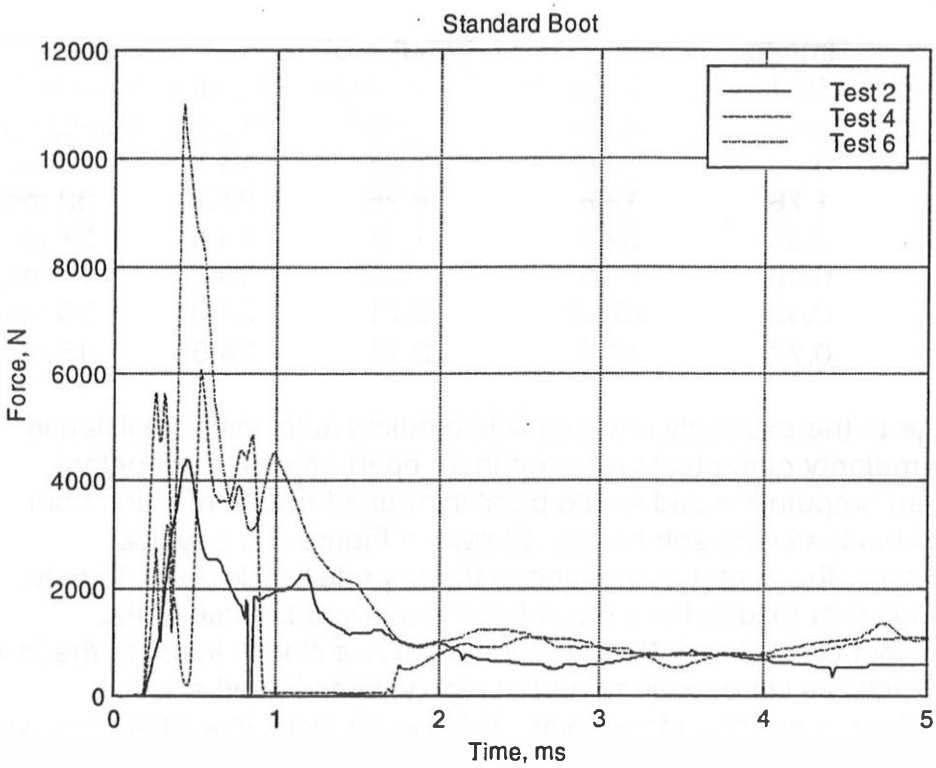


Fig. 3 - Force time traces for the U.S. Army standard combat boot

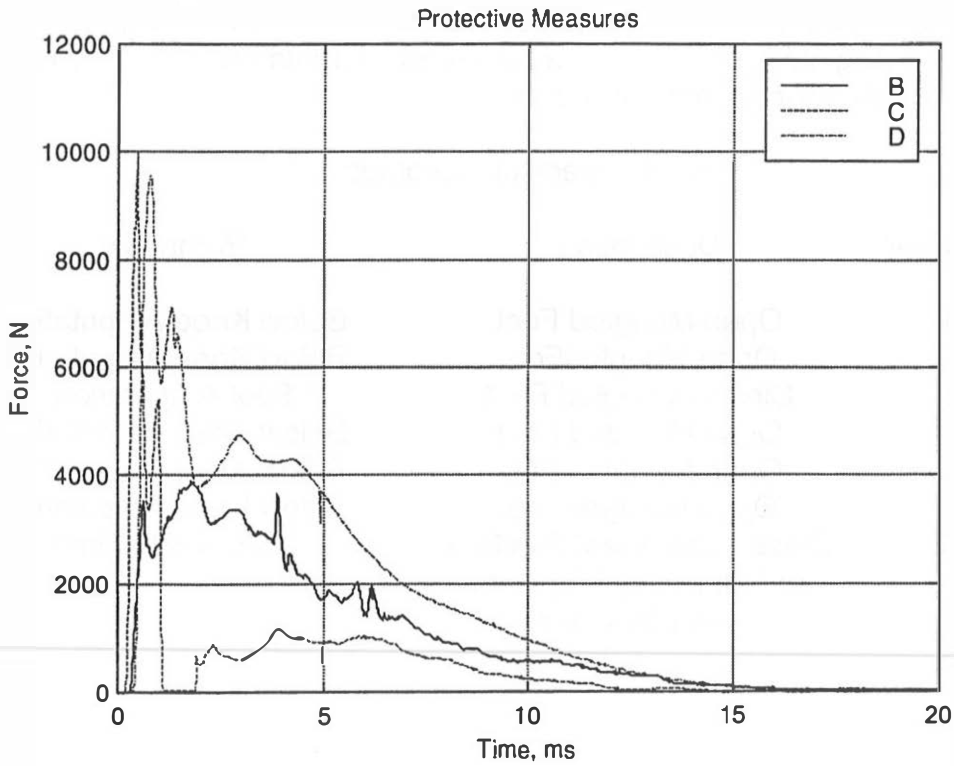


Fig. 4 - Force time traces for the various protective measures evaluated.

Table 6 – Loading rates and impulse data for all experiments

Test	Protective Measures	Time to Peak Force (ms)	Loading Rate (N/ms)	Impulse at Peak Force (N-sec)	Impulse (N-sec)	Time to Peak Impulse (ms)
2	A	0.45	22.0	0.56	13.3	50 ms
3	B	1.78	12.8	4.26	21.7	32 ms
4	A	0.53	89.1	1.01	18.5	27 ms
5	C	0.46	55.5	1.46	10.7	14 ms
6	A	0.42	137.7	0.71	24.0	50 ms
7	D	0.77	44.2	2.11	34.5	15 ms

The damage to the extremity and possible medical outcomes are listed in Table 6. The majority of the tests resulted in an open, mangled injury that would require an amputation and would be at increased risk of infection from dirt and foreign bodies in the soft tissue. Shown in Figure 5 is a typical radiograph showing the extent of damage to the unprotected lower extremity. The only subjects that resulted in a closed injury involved the use of the protective overboot (Test 3 and 7). Test 3 resulted in a closed injury to the foot and leg. The fractures were crushed and/or highly comminuted and not reconstructible from a surgical standpoint. This would result in a BKA, however the risk of infection would be greatly decreased when compared to an open blast injury. Test 7 resulted in a closed injury and a minimally displaced calcaneal fracture, possibly requiring repair and a non-displaced fracture of the talus that would probably heal without treatment. While the individual would be a combat casualty, the injury might allow for recovery in 4-6 months with surgical or non-surgical treatment. The non-surgical treatment would involve casting and crutches for up to three-months.

Table 5 – Medical outcomes

Test	Footwear	Description	Prognosis
1	A	Open Mangled Foot	Below Knee Amputation
2	A	Open MangledFoot	Below Knee Amputation
3	B	Closed Mangled Foot	Foot Amputation
4	A	Open Mangled Foot	Below Knee Amputation
5	C	Open Mangled Foot	Below Knee Amputation
6	A	Open MangledFoot	Below Knee Amputation
7	D	Closed Calcaneal Fracture and Minimally Displaced Talus Fracture	Salvagable Limb

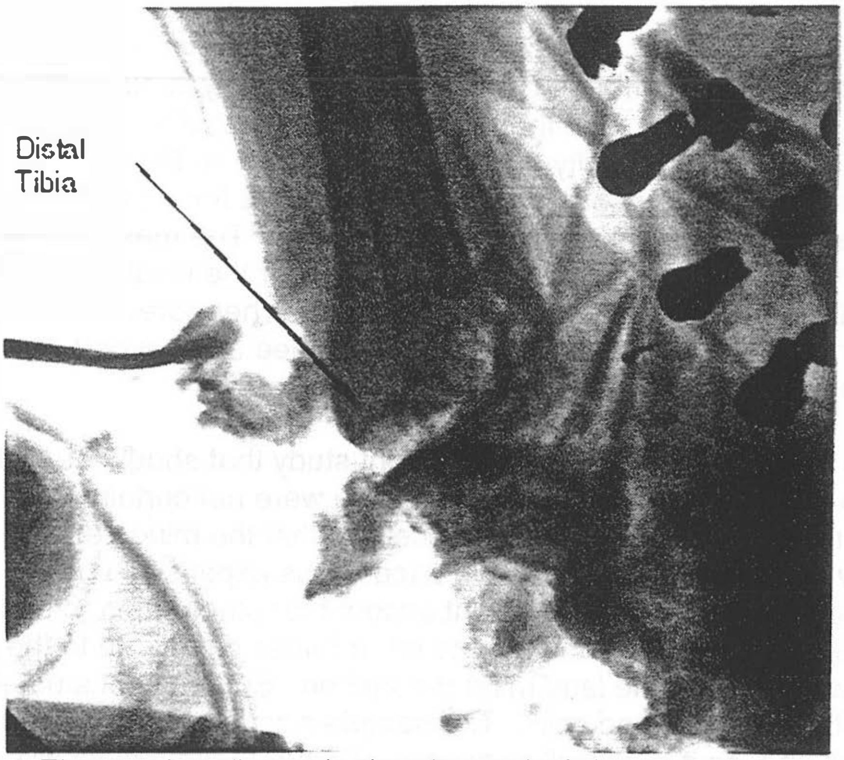


Fig. 5 – A radiograph showing typical damage to a foot that results from landmine detonation with a standard combat boot. The distal portion of the tibia is the only recognizable structure.

DISCUSSION

The objectives of our study were: a) to evaluate the relative protection offered by various combat footwear; b) to determine the *in-situ* forces and strains experienced by the lower extremity under blast conditions; c) to document the blast event, and d) medically evaluate the mine injury to the lower extremity that results from activation of a blast antipersonnel mine. Our results of this preliminary study suggest that practical mine protective measures may be feasible. The best results appear with blast protective boot/overboot combination. The largest force in the tibia we measured was 11000 N with a corresponding strain in the femur of 1650 $\mu\varepsilon$. Assuming a circular cross-section for the tibia with an outer and inner diameter of 20 mm and 12 mm, respectively, the peak stress is approximately 55 MPa. By assuming an elastic modulus for the femur of 25 GPa, the stress at the point of measured strain approximately 41 MPa. The difference in stresses in the tibia and femur are due to the fact that the force in the tibia is the *average* axial stress, resulting from the total axial force in the tibia. In the femur, the strains are measured only at a point, and does not account for the total axial loading component. In either case, the stresses are actually well below the failure strength of the bone, which are on the order of 130 MPa in tension, and 200 MPa in compression (Reilly and Burstein, 1975). This accounts for the fact that most of the damage resulting from the mine blast remains localized to the lower portion of the limb in the vicinity of the mine.

The detonation of a blast mine has several events beginning with a single positive pulse that radiates from the source with a velocity in air on the order of 1500 m/s, a negative phase, and then a mass movement of air behind the shock front with very high velocity and pressure, known as the dynamic pressure. The measured rise time and duration of the force pulses roughly correspond to those reported for detonations of TNT. The mass movement of air is capable of disintegrating tissue and accounts for the localization of the injury to the distal regions of the lower extremity. Furthermore, the contamination of the tissue, sometimes up to the knee and beyond, is a consequence of the blast wind.

There are some weaknesses of this current study that should be addressed. The load was only measured axially because we were not certain of the damage that may occur, and we were concerned that the mine detonation might destroy a load cell. Therefore, we used a less expensive uniaxial load cell, accepting the loss of data that might account for other damage to the bone. It is likely that torsion, bending and other forces contribute to the overall damage to the bone from the land mine detonation. Subsequent studies will be conducted with multi-axis load cells. The sample size for the boot/overboot combination is one, so it is difficult to assess whether these results will be valid for a population, or if we are just dealing with exceptional cases. However, noting that the cadavers were elderly males and females, suggests that younger individuals with higher bone quality will be more likely to sustain less damage to the bone from mine activation using the current protective footwear combinations.

A few trends seen in Tables 5 and 6 are that extent of injury is inversely correlated with impulse and loading rate, and positively correlated with time to peak events. This suggests that if the speed of the pressure wave could be slowed down, the damage to the limb can be lessened. The reason for the inverse correlation of higher impulses and forces with less damage is related to the fact that if the bone structure is not destroyed by the blast, it provides a structure to generate/resist force. Similarly, if the foot is destroyed by the blast, the energy of the blast is dissipated in the lower portion of the extremity, and does not provide a structure to transmit forces to the rest of the limb.

In order to be effective, antipersonnel-mine measures must provide a structure that can dissipate the blast energy without destroying the limb. In the case of our tests, this was obtained by the use of a composite overboot that is itself destroyed by the blast. In both cases in which the overboot was used, the injury to the lower extremity was closed. By using both the overboot and a blast protective boot, which contains additional energy dissipating composite materials and a blast deflective shield, the foot sustains damage that is operable. Even though the overall impulse transferred to the limb is more with the blast boot, the loads are distributed over a longer period of time and results is less overall damage to the bone.

The health consequences of landmines include deaths, injuries, disabilities, and enormous investments in health-care resources. Approximately one third of the landmine mine victims require amputations and often require a disproportionate amount of health-care resources and societal costs (Coupland 1996). Compared to other patients with war –related injuries, amputees require nearly three times as many units of blood and four times as many surgical procedures (Eschaya-Chauvin 1992). Any level of protection that can decrease the impact of injury to the lower extremity can have a positive impact on the victim and the health-care system. Our results suggest that antipersonnel mine protective footwear may be feasible; unfortunately, under conditions of mine activation, the footwear tested would still render the victim a mine casualty. However, the resulting injury may be amenable to retention of the limb/extremity, resulting in a lesser medical and societal cost.

REFERENCES

1) Cooper, G.J. Pearce B.P., Sedman A.J., Bush I.S. Oakley, C.W. Experimental evaluation of a rig to simulate the response of the thorax to blast loading. Vol 30(3), 1996, s38-s41.
2) Cooper, G.J., Townend, D.J., Cater, S.R., Pearce, B.P. The role of stress waves in thoracic visceral injury from blast loading: modification of stress transmission by foams and high-density materials. J Biomech, Vol 24(5), 1991, 273-285.
3) Coupland RM., The Effect of Weapons: Defining Superfluous injury and Unnecessary Suffering. Medicine and Global Survival 3 (A1), 1996.
4) Crandall, J. Personal communication, 1999.
5) Eshaya-Chauvin B, Coupland RM. Transfusion Requirements for the Management of War Injured: The Experience of the international Committee of the Red Cross. Br J Anaesth 68, 1992, 221-223.
6) Hull, J.B. Cooper G.J. Pattern and mechanism of traumatic amputation by explosive blast. J Trauma, Vol 40(3), 1996, s198-s205.
7) Jacobs L.G.H. The landmine foot: its description and management. Injury, Vol 22(6), 1991, 462-466.
8) Korver, A.J.H. Injuries of the lower limbs caused by antipersonnel mines: the experience of the International Committee of the Red Cross. Injury, Vol 27(7), 1996, 477-479.
9) Reilly, D.T. and Burstein A.H. The elastic and ultimate properties of compact bone tissue. J. Biomech, Vol 8(6), 1975, 393-405
10) Rutherford K, Hersman, J., Kowzlowiski A. Landmine Injuries 1993-1996 International Emergency and Refugee Health Vol8 (46), 1997,724-726.
11) Wertheimer, B., Lovric Z, Kresimir C., Kovac B, Kuvezdic H. Foot injuries caused by anti-personnel mines. Mil. Med Vol 160(4), 1995, 177-179.