Lower Leg Injuries in Dismounted Military Personnel from Buried Explosives

Karin A. Rafaels, PhD, Patrick J. Gillich, Rachel Z. Ehlers, Paul S. Duvall

Abstract Leg injuries, including traumatic amputations, from buried blasts are a significant injury, often resulting in the inability of the dismounted Soldier to return to duty. The soil from a buried charge contributes significantly to the injuries seen in the Soldier. The soil from a buried charge can interact through the soil bubble containing the detonation products acting as a piston, and/or the soil ejecta or particles that are thrown out after the bubble has burst impacting the individual. Building on previous landmine studies in which various legforms were placed directly over the charge, this study investigated injuries to surrogate lower legs that were at varied radial distances from the charge. Two different soil loading conditions and their contributions to injuries were explored. Equal charge sizes buried at different depths were detonated to expose up to four legs. Some of the legs were protected with a steel shield to reduce the impacts from the soil ejecta. Fracture patterns differed depending on the primary mechanism of soil loading. The fractures were seen higher on the leg when the primary loading mechanism was from the soil ejecta. Additionally, the distance from the charge affected the severity of injury.

Keywords blast injury, lower leg injury

I. INTRODUCTION

As of December 3, 2012, over 1,700 military servicemembers have sustained a battle-injury amputation in Operation Iraqi Freedom, New Dawn, and Enduring Freedom with most of the amputations resulting from explosive devices [1-2]. Because explosive devices found in the battlefield are commonly buried, the majority of the amputations are to the lower limbs [2]. Considering that amputations are life altering, costly, and diminish our military force [2], it is important to understand the mechanisms of these injuries and the radius of effectiveness of the explosive devices to determine how to reduce the occurrence of amputations.

The effective load, or impulse, from a buried charge that is delivered to the leg is likely to be correlated to the level of trauma. The two major contributions to the effective load are from the air shock and the momentum transfer from impact of the soil [3]. Stresses from the transmitted wave can shatter the lower limb, known as brisance [4]; and the forces from soil ejecta and detonation products can be transferred to the lower limb via conservation of momentum [5]. Experience from case studies and research show both shock waves and soil from a buried explosive can cause injury [6-10]. However, since shock waves decrease rapidly with distance and are almost entirely reflected back into the soil as a tensile wave, the most significant loading results from the momentum transfer of the soil [9]-[11]. The soil from a buried charge can interact with an object in several ways: the soil bubble containing the detonation products can act as a piston, and/or the soil ejecta or particles that are thrown out after the bubble has burst can impact the object. When an object is close to the detonation, both types of soil-loading mechanisms can occur. By exploring positions that are not directly over the charge, an investigation to understand the contribution of each type of loading can be explored and discussed.

Opportunely, landmine research has already developed various tools and performed research for evaluating lower extremity injuries from blast mines, including mechanical legs, frangible legs and biological specimens [12]. Each type of leg surrogate has its strengths, so the selection of the appropriate leg surrogate requires trade-offs. The mechanical legs are simple, reusable and therefore cost-effective, but they do not provide detailed information about injuries. Biological specimens, such as human cadavers, have a high degree of variability and are difficult to instrument without compromising the tissue; however, they are structurally, kinematically and kinetically similar to living human tissue. Frangible legs provide a more repeatable, geometrically similar and, relatively, structurally similar model for the human leg which can more easily be

All authors are scientists in the U.S. Army Research Laboratory at Aberdeen Proving Ground, MD. K. A. Rafaels, a Biomedical Engineer, is the corresponding author (tel: 410-278-9459, fax: 410-278-4123, karin.rafaels@us.army.mil).

instrumented than biological specimens. Consequently, a frangible leg surrogate was chosen for these experiments, of which the results will be analyzed and evaluated in this manuscript. Using the frangible leg surrogate, a minimum radius of injury from buried explosives will be studied.

II. METHODS

eFSLLM's, or enhanced Frangible Surrogate Lower Legs – Modified, (Adelaide T&E Systems, Torrensville, South Australia) were used to simulate human legs in the buried explosive experiments (Figure 1). The legs have been designed and validated against anti-personnel and anti-vehicular landmine experiments [13]-[5], a loading regime similar to the explosive experiments in this study. Additionally, this lower leg surrogate is designed to be anthropometrically-correct below the mid-tibia. This feature allows for some sensitivity to the impact location on the foot, which may be important since location of loading affects the types of injuries that can occur [14]. Furthermore, the eFSLLM has the ability to obtain physical measurements, such as strains and loads, for correlations with injury. The strain gauge instrumentation was designed to differentiate between compressive and bending loads by mounting them on a region of the leg that has geometric symmetry. This modification to the leg geometry allows the computation of the compression load by adding opposite signals and the computation of bending by subtracting the signals. More details on the design of the legs can be seen the Footner *et al.* reference [13].

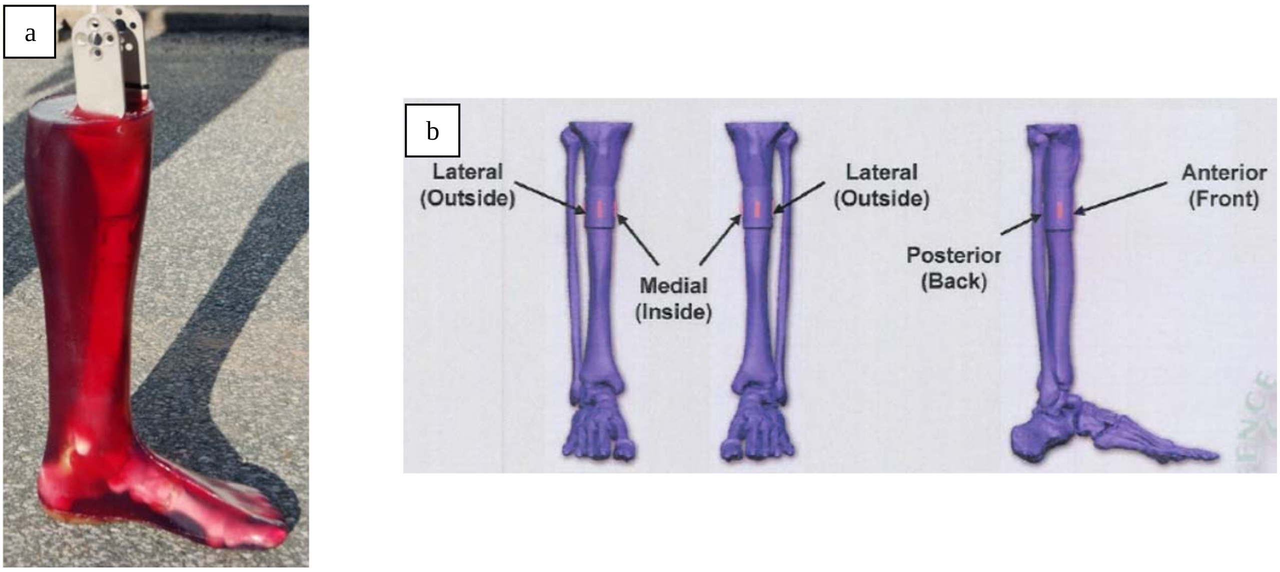


Figure 1. enhanced Frangible Surrogate Lower Leg – Modified (eFSLLM). a.) Photograph of eFSLLM. b.) Schematic of the eFSLLM and strain gauge locations.

Figure 2 shows a schematic for the generic experimental setup for the tests. All of the experiments were conducted on a large, raised, and level berm contained in a concrete box with dimensions 50 ft x 40 ft x 8 ft deep. Steel support towers were constructed at two edges of the concrete box to allow for steel, overhead cables to run across the length of the box near the area of detonation. Guide lines were hung down from these overhead cables to stabilize and hold each surrogate leg in place, but were not meant to support the weight of the legs. Steel weights were mounted to the knee clevis of the eFSLLM to obtain a reaction mass of 90 lb, representing half of the body mass for a 50th percentile male, the amount of weight one leg would typically support when standing. The legs were positioned at various distances from the center of the charge with their heels closest to the detonation point since the eFSLLMs are more biofidelic in the heel than at the forefoot. All of the legs were dressed in US standard issue combat boots and uniforms. To investigate the two soil-driven mechanisms of injury, some legs were protected by a large, steel deflector which protected the leg from the soil ejecta. In Figure 3 the experimental setup of the lower leg surrogates with a steel deflector is shown.

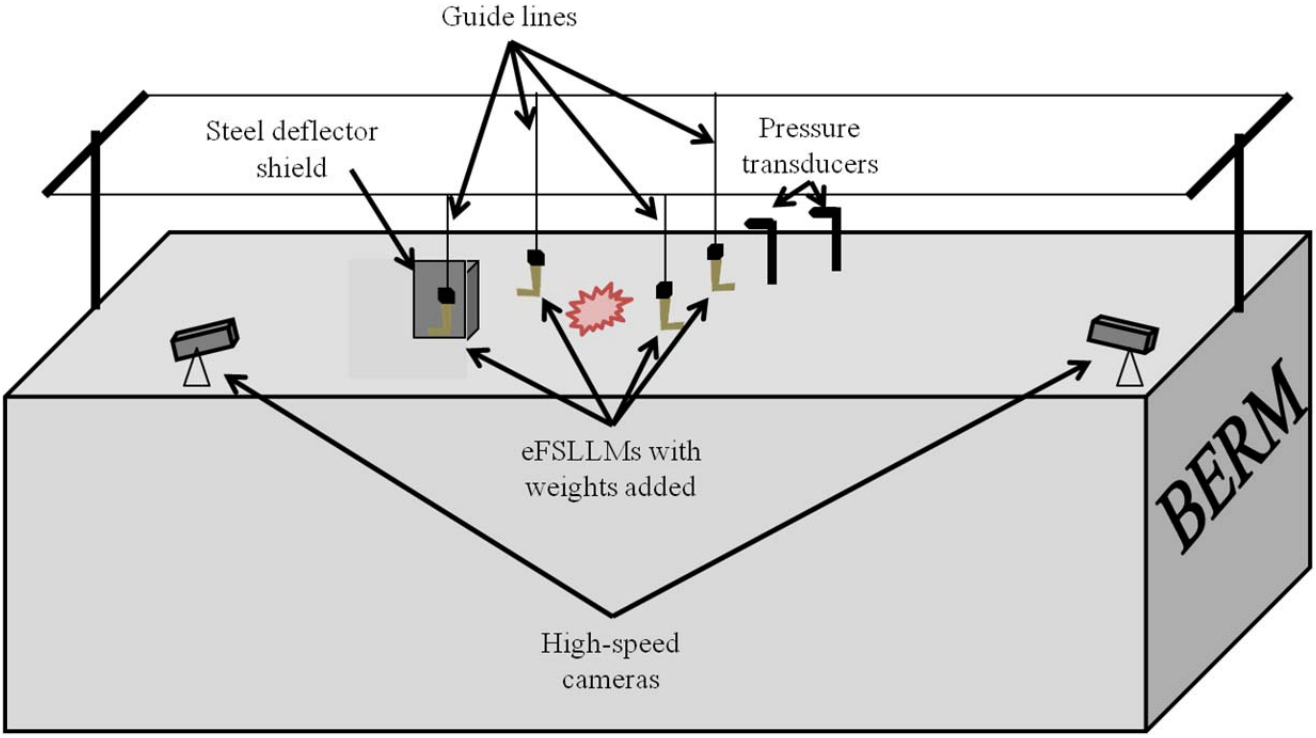


Figure 2. Schematic for the experimental setup for buried blast tests with surrogate legs.

Figure 3. Experimental setup of test with the deflector.

The surrogate legs were added to an existing experimental series with buried explosives. The explosive conditions used for the leg tests involved the same explosive buried at two different depths in two different soil types. Previous buried blast research has shown that similar loading can be achieved with the same charge size at different burial depths [15-16]-[9], where the contribution of the air shock increases as the depth of burial decreases [17]. Leveraging data obtained on small-scale, buried explosive experiments with similar impulses carried out by our organization and using the Hopkinson scaling laws for distance, the two burial depths selected for the inclusion of surrogate legs were chosen to provide different mechanisms of loading for similar impulses. Additionally, since various soil types can affect the amount of momentum transfer to objects [18-19], two different soil types were also selected. Soil Type 1 can be described as a brown, clayey, silty sand with slight or low plasticity and low concentration of gravel. Soil Type 2 is a clean, silty sand with particles no larger than 4.75mm and no smaller than 0.075mm in a single grain soil structure.

Air pressure measurements were taken using piezoelectric pressure sensors (model 137; PCB Piezotronics, Depew, NY) placed at 2 m and 3 m from the center of the charge. All of the data (pressure and strain gauge) was sampled at 1 MHz with a 40 kHz Butterworth filter. Soil velocities for each test were calculated by tracking the outermost points/pixels in the expanding soil cloud from the high-speed camera (NAC Memrecam GX-3 model #V-190, NAC Image Technology, Simi Valley, CA) images, sampled between 5000 and 6000 frames per second, using ProAnalyst software (Xcitex, Inc., Cambridge, MA). The pixel scaling in the images was determined by obtaining images before the experiment with a calibration tool of known dimensions in the same plane as the center of the explosive.

The primary method for injury evaluation was by inspection of radiographic images of the legs. Still photographs were also taken post-shot. Further insight into the injuries was provided by the four strain gauges mounted to the upper tibia of the eFSLLMs, which have been calibrated to record tibial axial compression and medial/lateral and anterior/posterior bending. Leg injuries were scored for comparisons using two injury scales, the Mine Trauma Score (MTS) and the Bone Damage Response Scale (BDRS) for the Surrogate Lower Leg [12]. The MTS was adjusted so that the scores were entirely numerical for ease of analysis. Descriptions of the injury scales are provided in Tables 1 and 2. The leg surrogate is not designed to predict soft tissue injury; however, if the lower leg was separated from the rest of the surrogate, it was considered to be an open and contaminated injury.

TABLE I

Definitions of the Mine Trauma Score [12]

Score	Adjusted Score	Injury	Level of amputation required
0	0	Minimal	No major injury
1	1	Closed	Salvageable limb
1A	1.33	Open contained	
1B	1.67	Open contaminated	
2	2	Closed	Below knee amputation
2A	2.33	Open contained	
2B	2.67	Open contaminated	
3	3	Open contaminated	Below or above knee amputation
4	4	Open contaminated	Above knee amputation

TABLE II

Bone Damage Response Scale for the Surrogate Lower Leg

(Calcaneus, Talus, Tibia/Fibula) [12]

0	No Damage	
1	Single Fracture	
2	Multiple Fractures, Non-Displaced	Difficult, but may heal
3	Comminuted Fracture (Displaced)	Potential blood supply difficulties
4	Destroyed/Eroded	
mm	Location of Fracture (Tibia/Fibula)	Measured from knee joint

III. RESULTS

The measured peak air overpressure, air impulse and soil velocity increased when the depth of burial decreased. The relationship between these blast exposure parameters and the soil types, however, was not consistent. Table 3 provides the experimental conditions and injury results for each test. Leg number 3 was thrown from the test pad and never recovered so no injury results could be determined. Not surprisingly, the surrogate legs demonstrated increased injury severity as the leg was positioned closer to the charge as exhibited in Figure 4. This phenomenon was true regardless of scoring method, soil type or burial depth. A typical injury included a pilon, or distal tibia, fracture with an additional complete, transverse fracture of the tibial shaft (Figure 5). Five of the nineteen recovered legs were traumatically amputated.

TABLE III
Experimental Conditions and Injury Results

Leg Number	Soil Type	Burial Depth	Standoff (ft)	Shielded	MTS – Adjusted	BDRS
1	Type 1	Shallow	1	No	6	3
2	Type 1	Shallow	3	No	1	1
3	Type 1	Shallow	2	No	NA	NA
4	Type 1	Shallow	4	No	0	0
5	Type 1	Deep	1	No	7	3
6	Type 1	Deep	2	No	6	3
7	Type 1	Deep	3	No	1	1
8	Type 1	Deep	4	No	1	2
9	Type 2	Shallow	2	No	7	3
10	Type 2	Shallow	8	No	0	0
11	Type 2	Shallow	4	No	0	0
12	Type 2	Shallow	6	No	0	0
13	Type 2	Deep	2	No	7	3
14	Type 2	Deep	4	No	0	0
15	Type 2	Deep	6	No	0	0
16	Type 2	Deep	8	No	0	0
17	Type 2	Shallow	2	No	3	2
18	Type 2	Shallow	2	Yes	1	2
19	Type 2	Deep	2	Yes	1	3
20	Type 2	Deep	2	No	1	2

Soil Type 1 has a greater density than Soil Type 2.

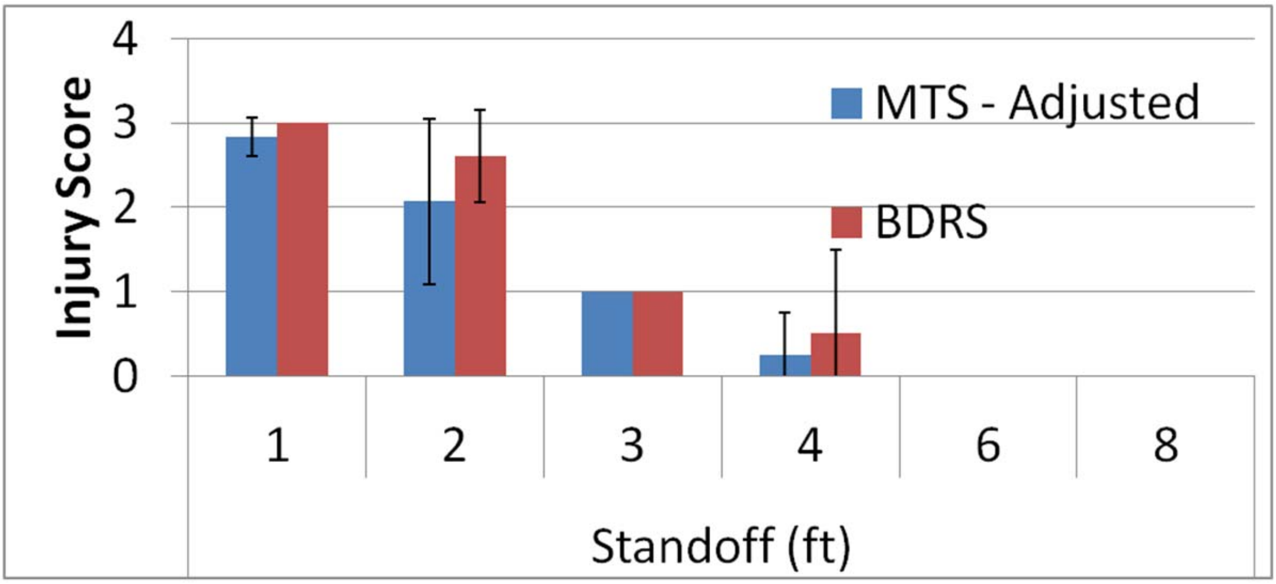


Figure 4. Average unprotected surrogate lower leg injury scores at various radial standoff distances from charge.

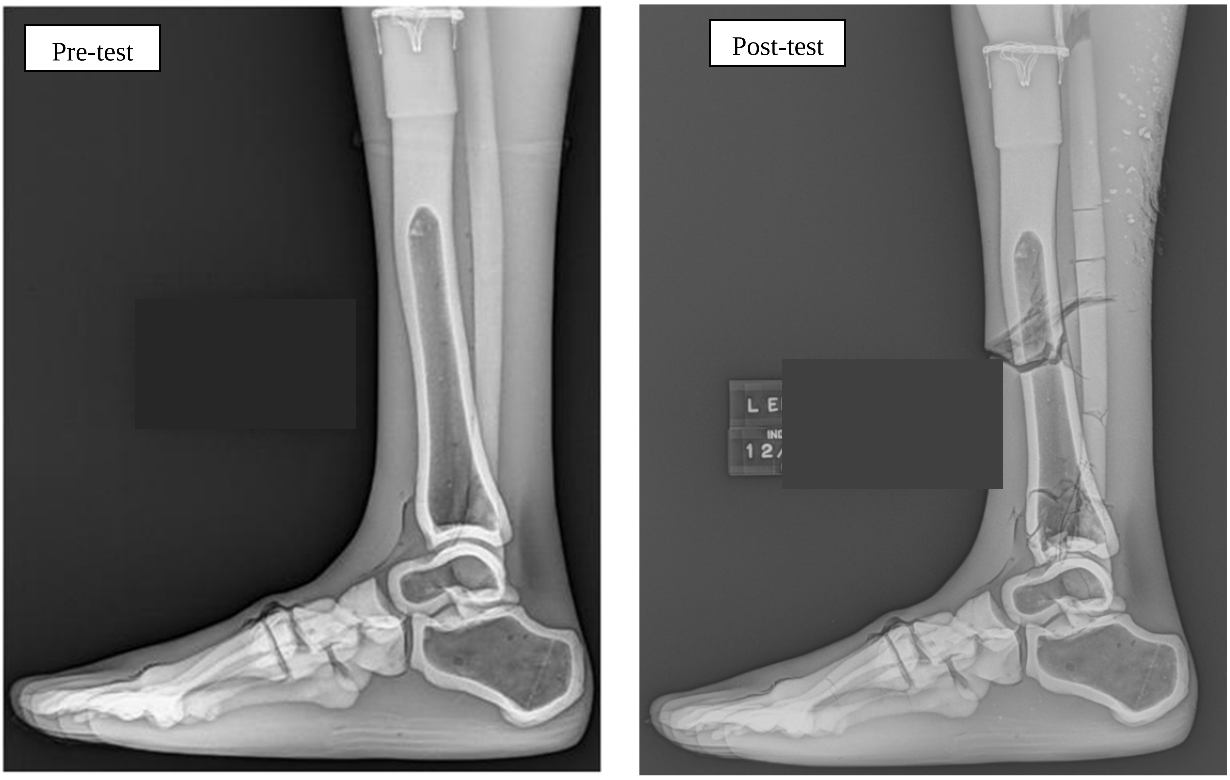


Figure 5. Radiographic images of the surrogate legs. The first figure on the left is a pre-test image. The figure on the right shows a typical post-test x-ray image of a surrogate leg demonstrating the pilon and tibial shaft fractures. These images are from Leg 17.

Generally, as the soil velocity at initial impact increased, the severity of the injuries increased. However, the trend was more pronounced for the deeper burial depths. Figures 6 and 7 display the injury severity using the two injury scales with respect to the peak velocity of the soil at initial contact with the surrogate leg.

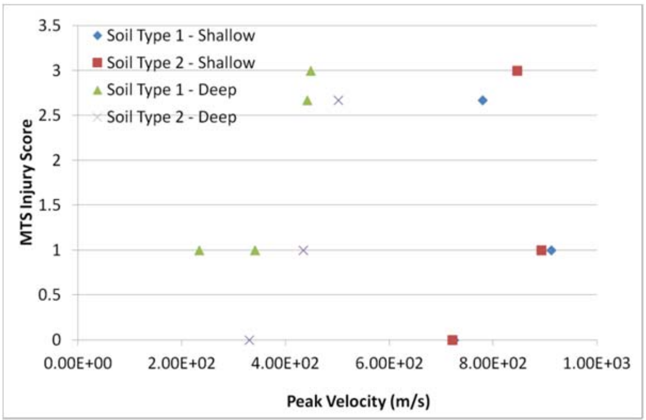


Figure 6. Injury severity using the MTS as a function of the peak soil velocity at initial contact with surrogate leg.

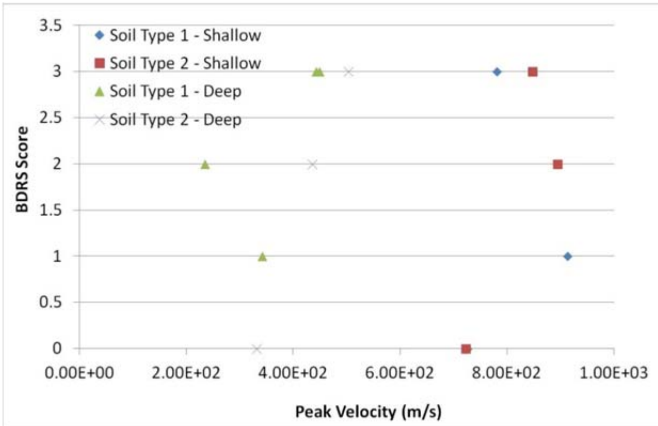


Figure 7. Injury severity using the BDRS as a function of the peak soil velocity at initial contact with surrogate leg.

The strain gauges mounted on the proximal tibia provided some useful information, but did not always correspond to the damage levels witnessed in the legs. The medial gauge was the most frequent gauge to indicate breakage first. Interestingly, the anterior gauge was the first to break for each of the shielded tests; however, the posterior gauge was not functional in one of those two tests. The peak measured axial loads for the shielded legs were an order of magnitude lower than the unshielded legs at the same standoff regardless of the burial depth for the same soil type as seen in Figure 8. The signals from the strain gauges representing the bending forces comparing the shielded legs with the unshielded legs at the shallower burial depth are presented in Figure 9. Similar to the shallow buried case, the bending loads of the shielded leg are very minimal compared to the unshielded legs. Conditions in which the primary loading mechanism was from the soil ejecta and not the soil bubble, the magnitudes of the loads measured on the gauges of the legs were higher, as indicated in Figures 10-12. Figure 13 shows the typical injury from the soil bubble loading, whereas Figure 14 displays the typical injury from soil ejecta as the primary loading mechanism.

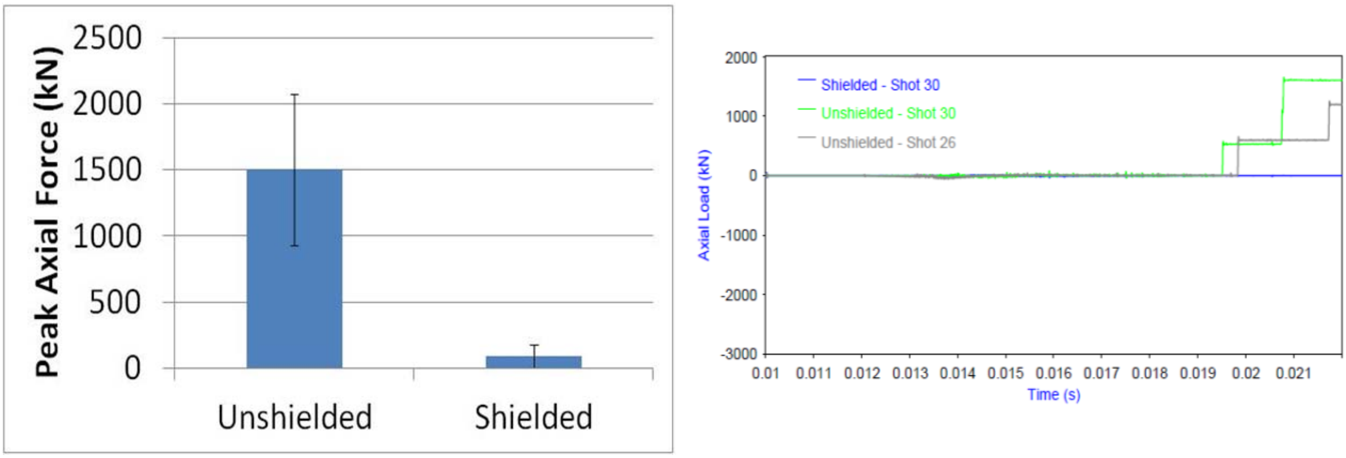


Figure 8. The figure on the left shows the average peak axial force measured by the strain gauges for unshielded and shielded legs at 2 ft standoff for soil type 2. The unshielded legs displayed significantly higher peak axial forces than the shielded legs. The figure on the right shows the traces from both shielded and unshielded legs for the same exposure condition. All of the depicted legs were fractured upon post-test examination, yet only the unshielded legs demonstrated breaks in the gauges (indicated by the step rises in the traces). The explosive was detonated at time = 0.01 s.

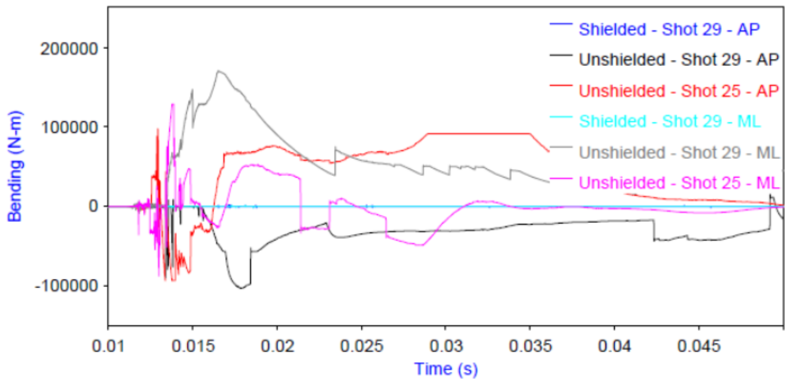


Figure 9. The bending load traces for the shielded and unshielded legs at a 2 ft standoff, buried shallowly in soil type 2. The strain gauges in the unshielded legs measured significantly higher bending loads than the shielded leg. The explosive was detonated at time = 0.01 s.

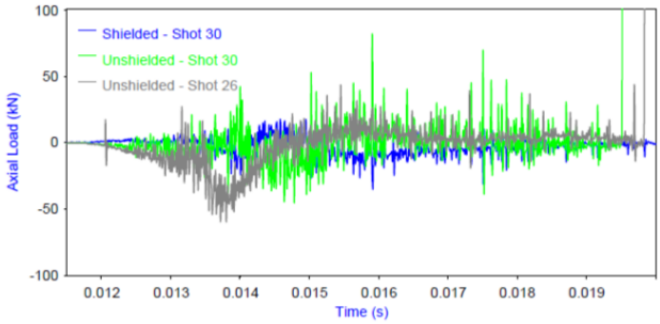


Figure 10. The axial loading traces for the deeper buried charge at 2 ft standoff in soil type 2. The measured magnitudes of the loads for the unshielded legs are greater than the shielded leg. The explosive was detonated at time = 0.01 s.

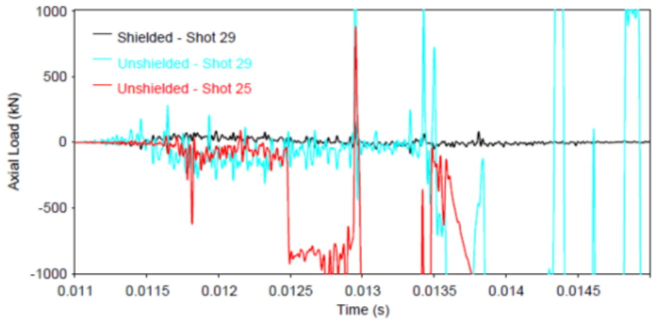


Figure 11. The axial loading traces for the shallower buried charge at 2 ft standoff in soil type 2. The measured magnitudes of the loads for the unshielded legs are greater than the shielded leg. The explosive was detonated at time = 0.01 s.

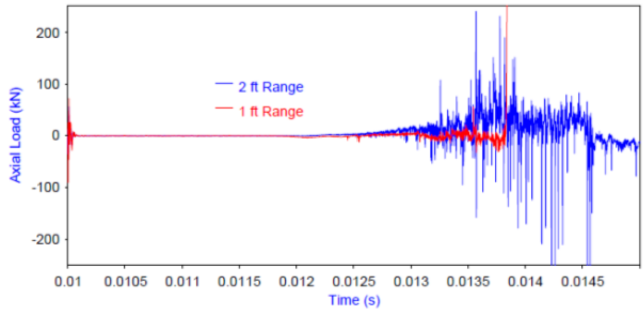
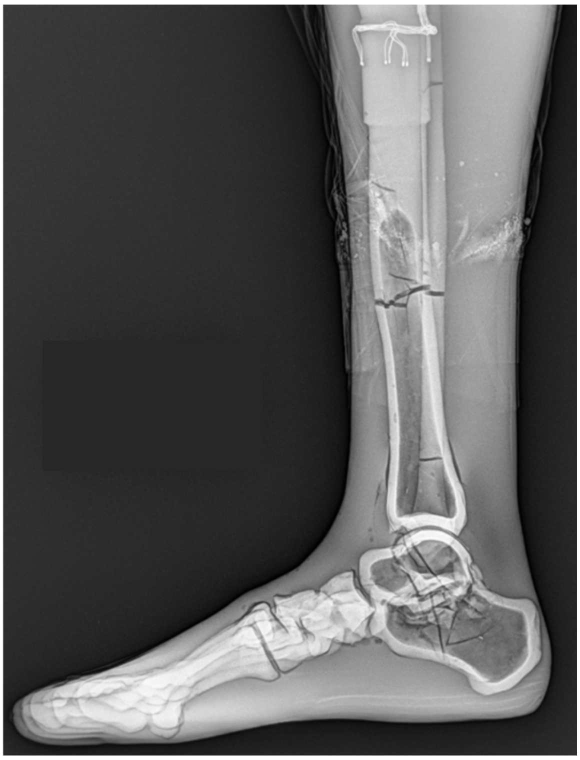


Figure 12. The axial loading traces for the deeper buried charge of soil type 1. The leg positioned at 1 ft experienced the majority of loading from the soil bubble, whereas the leg positioned at 2 ft experiences the majority of loading from the soil ejecta. Again, the strain gauges in the soil ejecta impacts measure greater magnitude loads than the impacts from the soil bubble. The explosive was detonated at time = 0.01 s.



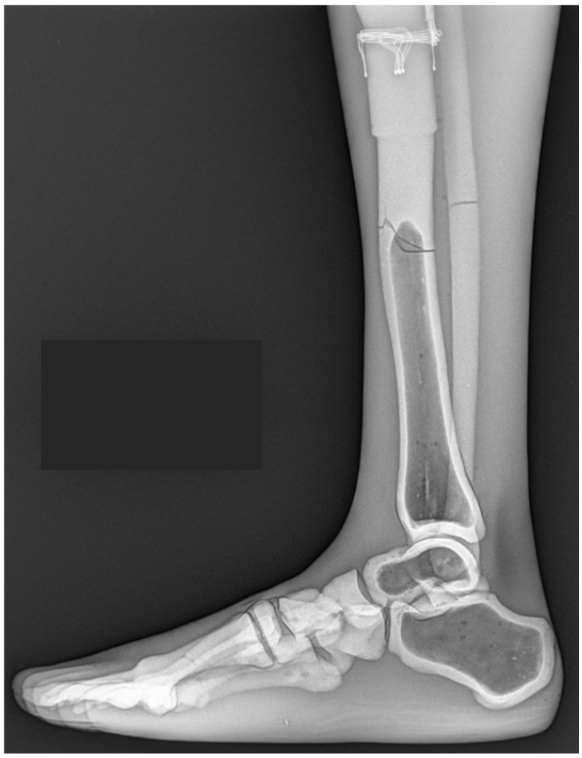


Figure 13. Radiographic image of Leg 19, a test condition in which the soil bubble was the primary

Figure 14. Radiographic image of Leg 2, a test condition in which the soil ejecta was the primary

loading mechanism. The calcaneus and talus are typically both fractured when the majority of the loading is from the soil bubble.

loading mechanism. The tibial shaft typically fractures when the majority of the loading is from the soil ejecta.

IV. DISCUSSION

Injuries to the lower limbs from an exposure to a buried blast were investigated. Experimental studies using human cadavers and surrogate legs have shown extensive damage to the lower extremity when the charge is buried directly under the heel [5]-[12]-[14]-[20]. This study focused on the resulting injuries when the foot is not directly over the charge. The fracture patterns witnessed in this study were different than those seen in human cadaver tests where the calcaneus and talus were often destroyed. In our study, the calcaneus and talus were only fractured in two legs, and only one of them demonstrated severe comminution. However, this may be an artifact of the surrogate legs chosen. Bergeron *et al.* concluded in their assessment of lower leg injuries from landmines that the calcaneus and talus were too rigid in the FSL leg model, a precursor to the eFSLLM used in this study [5]. The pad of the foot as well as the calcaneus and talus have been modified in the newer eFSLLM to try to correct for a less than ideal response, though it appears that it may still be a concern. Compared to other surrogate leg tests, the injuries in this study indicate that the loading conditions are different and not as severe since the locations of bone fracture differed and the overall injury severity scores were lower. The number of amputations and the involvement of the ankle joint were far reduced in this study.

By moving the legs away from the center of the charge, the soil ejecta played a larger role in the loading on the legs. Because the soil ejecta cloud radiates out from the center of the charge, the leg is initially loaded higher up on the leg, along the tibial shaft, compared to previous experimental studies. Figure 15 exhibits the initial soil ejecta cloud interaction with the leg. The soil ejecta interaction with the leg at a higher location may explain the higher frequency of tibia and fibula fractures without any calcaneus or talus fractures witnessed in these experiments compared to previous studies of buried blast leg injuries. The reaction mass placed on top of the legs acted as a concentrated axial load and the soil ejecta acted as a transverse load. The lateral loading of the soil ejecta deflects the leg and the reaction mass pushing down produces a bending moment. The fractures along the tibia and fibula fractured near the center of the leg where the bending moment would be maximal. It is important to note that the fractures witnessed at the higher locations of the leg come with a caveat. Since only the lower portion of the leg is considered anatomically correct, the fracture can only be used to indicate that the forces were large enough to break the surrogate leg, but no conclusions can be drawn on the actual loads necessary to fracture a human leg.

Figure 15. A frame from the high-speed video demonstrating that the soil ejecta cloud radiates out of the ground over the center of the charge. The interaction of the cloud and the leg in this experiment occurs along the tibial shaft, which is unlike the loading conditions from the previous landmine experiments where the leg is directly over the charge.

The legs that are close enough or are shielded from the initial interaction with the soil ejecta receive the majority of the loading from the soil bubble. These legs demonstrate fractures to the lower bones, such as the calcaneus or talus. Figure 16 shows two scenarios where the legs were initially loaded by the soil bubble and their resulting radiographic images. For the experiments that the legs were placed directly over the charge, the soil bubble provides the initial and the majority of the loading. It is, therefore, not surprising that the fracture patterns in the legs subjected primarily to the soil bubble loading are similar to the injury results in the literature for landmine.

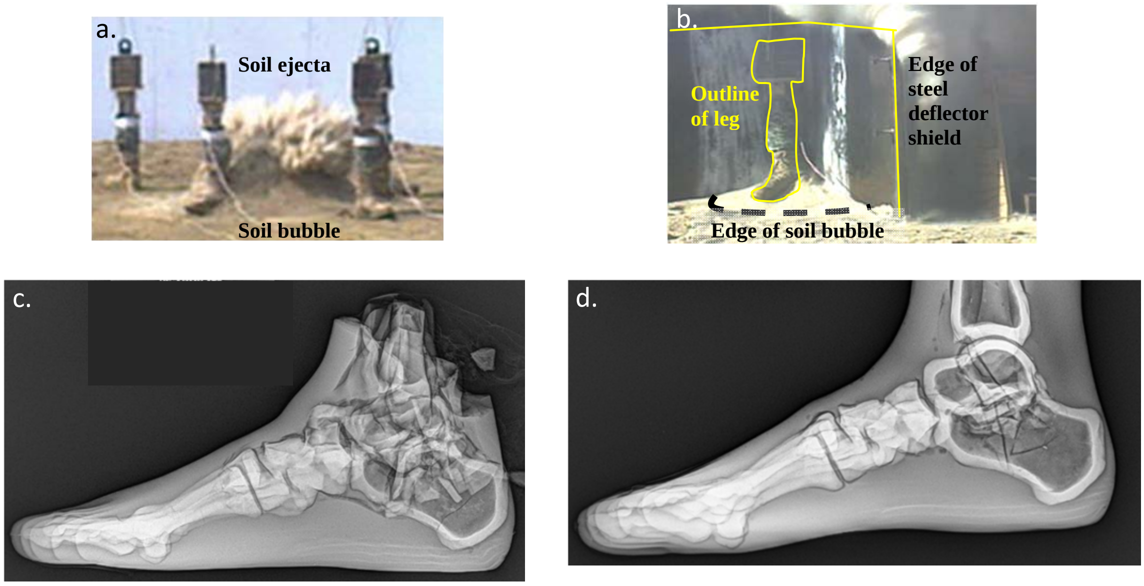


Figure 16. Injuries associated with the soil bubble interaction as the primary loading mechanism. Figures a and b display the interaction of the legs with the soil bubble from the high-speed video. Figure c is the radiographic image of the injured leg from the interaction in a; Figure d is the radiographic image of the injured leg from the interaction in b.

The velocity of the soil ejecta cloud, an approximation of the particle velocities in the ejecta available for impact with the leg, generally corresponded with the severity of the injuries. Since momentum is equal to the mass of the object times its velocity, as the velocity increased, the momentum transfer of the impacting soil particles would be larger, resulting in more severe injuries. For deeper burial depths, the velocity was positively correlated with injury severity; however, this positive correlation was not true for all of the shallower burial depth conditions. The deeper a charge is buried, the more energy is absorbed by soil compression and deformation. Consequently, the available energy to propel the soil ejecta is limited once the soil bubble has been breached. Conversely, if the charge is buried more shallowly, the compression wave from the detonation transmits less energy to the ground and the reflected tensile wave can contribute more to the push of detonation products to send ejecta out from the soil. At shallow enough depths, the peak velocities of the soil particles can continue to increase for several milliseconds. For the shallow burial depths used in this study, the closer legs were impacted before peak velocities were reached, indicating that more energy was available to cause damage to the legs. Whereas for the farther legs, although the particle velocities were faster at initial impact, the available energy behind the particles was not as large resulting in less severe injuries.

The strain gauges are mounted at the proximal tibia in the anterior, posterior, medial and lateral sides of the eFSLLM. The gauges provide a local strain and are not sensitive to the shock loading that is localized to the lower portion of the lower limb. Consequently, even though the load levels measured at the strain gauges were minimal for the tests involving the shield, the injuries to the lower limb were often more severe than the unshielded conditions. To better resolve the differences in loading between the soil ejecta and the soil bubble, more information is needed about the strains and/or loads near the ankle, which the current surrogate legform cannot provide. Furthermore, the peak loads did not correlate with injury severity since the surrogate legform could not capture the loads far from the gauges as accurately. On the other hand, the strain gauges were able to provide timing information that was useful for analysis.

One of the main limitations of this study is the small sample size. Full scale blast tests are expensive and complex. To reduce some of these impediments to testing, the legs were inserted into an existing test program, limiting the conditions to be evaluated. Futhermore, the legforms are not as structurally, kinetically or kinematically as biofidelic as human cadaver limbs would be. In addition to the potentially overly strong calcaneus and talus, the eFSLLM cannot properly reproduce soft tissue injury, a unique attribute to blast loading compared to blunt loading. Future tests should include more repeat conditions to be able to make sound conclusions and possibly use human cadavers to increase the biofidelity of the injury response. Improvements to the instrumentation on the eFSLLM would also increase the understanding of the loading conditions.

V. CONCLUSIONS

The results demonstrate that there may be two distinct loading pathways for lower leg injuries from buried blasts, although further research remains. The results also show that the eFSLLM can be used to distinguish between the two injury mechanisms, but could be improved upon to provide more loading information and a more biofidelic response. This study also reiterates the point that the chance of severe injury reduces as standoff from the detonation location increases.

VI. ACKNOWLEDGEMENT

The authors would like to thank Joel Stewart, Jillian Mills, Anthony Daly, James Racine, Patrick Woodie, Charles Wilhelm and Jason Garvey for their assistance in test design, test execution and blast data analysis for the experimental trials at Aberdeen Proving Ground, MD. Many thanks to Wes Fisk and David Thompson from Adelaide T & E Systems for their help and guidance in using the eFSLLM. The authors would also like to thank the Office of the Armed Forces Medical Examiner for their analysis of the radiographic images, and Nitin Moholkar and Kathryn Loftis for their consultation on the leg injuries. The financial support from the Joint Trauma Analysis and Prevention of Injury in Combat is kindly acknowledged.

VII. REFERENCES

[1] Fischer H, "Congressional Research Service Report: U.S. Military Casualty Statistics: Operation New Dawn, Operation Iraqi Freedom, and Operation Enduring Freedom" Internet: [http://www.fas.org/sgp/crs/natsec/RS22452.pdf], February 5, 2013 [accessed March 13, 2013].

[2] Krueger CA, Wenke JC, Ficke JR, Ten years at war: Comprehensive analysis of amputation trends, *J Trauma Acute Care Surg, 2012*, 73(6, Supp. 5):S438-S444, 2012.

[3] Fairlie G, Bergeron D, Numerical simulation of mine blast loading on structures, *Proceedings of the 17th International Military Aspects of Blast and Shock Symposium,* Las Vegas, USA, June 2002.

[4] Ramasamy A, Hill AM, *et al.*, Blast-related fracture patterns: a forensic biomechanical approach, *J. R. Soc. Interface*, 8:689-698, 2011.

[5] Bergeron DM, Coley GG, Fall RW, Anderson IB, Assessment of lower leg injury from land mine blast – Phase 1: Test results using a frangible surrogate leg with assorted protective footwear and comparison with cadaver test data (DRDC Suffield TR 2006-051), Suffield, Canada, February 2006. Internet: [www.gichd.org/fileadmin/pdf/LIMA/AssessmentLowerLeg1.pdf] [accessed June 24, 2013].

[6] Patel HDL, Dryden S, Gupta A, Ang SC, Pattern and mechanism of traumatic limb amputations after explosive blast: Experience form the 07/07/05 London terrorist bombings, *J Trauma Acute Care Surg,* 73(1):276-281, 2012.

[7] Hull JB, Cooper GJ, Pattern and mechanism of traumatic amputation by explosive blast, *J Trauma,* 40(3, March Supp.): S198-S205, 1996.

[8] Trimble K, Clasper J, Anti-personnel mine injury; Mechanism and medical management, *J R Army Med Corps,* 147:73-79, 2001.

[9] Bergeron DM, Tremblay JE, Canadian research to characterize mine blast output, *Proceedings of the 16th International Military Aspects of Blast and Shock Symposium,* Oxford, UK, September 2000.

[10] Coupland RM, Korver A, Injuries from antipersonnel mines: the experience of the International Committee of the Red Cross, *BMJ,* 303:1509-1512, 1991.

[11] Grujicic M, Pandurangan B, Huang Y, Cheeseman BA, Roy WN, Skaggs RR, Impulse loading resulting from shallow buried explosives in water-saturated sand, *Proc IMechE Part I: J. Materials Design and Applications,* 221:21-35, 2007.

[12] Cronin DS, Williams K, Salisbury C, Physical surrogate leg to evaluate blast mine injury, *Mil Med,* 176(12):1408-1416, 2011.

[13] Footner MJ, Bergeron DM, Swinton RJ, Development and calibration of a frangible leg instrumented for

compression and bending (DSTO-TR-1829), Edinburgh, Australia, February 2006. Internet: [http://dspace.dsto.defence.gov.au/dspace/bitstream/1947/4420/1/DSTO-TR-1829%20PR.pdf] [accessed June 24,2013].

[14]Bass CD, Folk B, *et al*., Development of a test methodology to evaluate mine protective footwear, *Proceedings for the 24th Army Science Conference,* Orlando, FL, USA, 29 Nov-2 Dec 2005.

[15]Uribe JAH, Poveda VHB, Rodriguez JPC, Effect of set up parameters of landmine blast over transferred energy to a rigid body: experimental and computational study, *Proceedings of the 26th International Symposium on Ballistics,* pp. 187-195, Miami, FL, USA, September 2011.

[16]Fourney WL, Leiste U, Bonenberger R, Goodlings DJ, Mechanism of loading on plates due to explosive detonation, *Fragblast,* 9(4):205-217, 2005.

[17]Borvik T, Olovsson L, Hanssen AG, Dharmasena KP, Hansson H, Wadley HNG, A discrete particle approach to simulate the combined effect of blast and sand impact loading of steel plates, *J. Mech. Phys. Solids*, 59:940-958, 2011.

[18]Hlady SL, Effect of soil parameters on land mine blast, *Proceedings of the 18th International Military Aspects of Blast and Shock Symposium,* Bad Reichenhall, Germany, September 2004.

[19]Hinz B, Muci-Kuchler K, Muci M, Cheeseman BA, Effect of sand type and standoff height on momentum transfer in a shallow buried compressed gas blast, *Proceedings of the 81st Shock and Vibration Symposium,* Orlando, FL, USA, October 2010.

[20]van der Horst M, Dijkstra M, van de Kasteele R, Luiting M, Mine boot testing and evaluation using two different surrogate legs, *Proceedings of the Personal Armour Systems Symposium,* Brussels, Belgium, October 2008.