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Lower Extremity Assistance for Parachutist (LEAP) Program: Quantification of the Biomechanics of the Parachute Landing Fall and Implications for a Device to Prevent Injuries

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13. ABSTRACT *(Maximum 200 words)*

This report presents results from two experiments conducted for the lower extremity assistance for parachutist (LEAP) program. These experiments are part of a systematic effort to develop a device to prevent lower extremity injuries to airborne soldiers. To develop such a device, data were collected about the biomechanics of the parachute landing fall (PLF). The data collected included ground reaction forces, ground reaction moments, and displacements of the soldier's lower extremities as he performed a PLF. The experiments were conducted in an indoor laboratory. Test participants jumped from platforms onto a force plate. Their motions were recorded by video cameras as they performed PLFs. In the first experiment, biomechanical data about PLFs in five legwear conditions were collected: boots, ankle braces, knee braces, ankle and knee braces together, and viscoelastic material covering the force plate. Based on the significant impact reduction of the viscoelastic material, prototype impact-absorbing soles were developed and then tested in the second experiment. The impact-absorbing soles provided significant reductions in impact forces and moments compared to jumps in boots only. Development of a protective device should begin with impact-absorbing soles. Then, braces that protect the joints and allow natural motions should be developed and integrated into a complete lower extremity protective device.

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LOWER EXTREMITY ASSISTANCE FOR PARACHUTIST (LEAP) PROGRAM: QUANTIFICATION OF THE BIOMECHANICS OF THE PARACHUTE LANDING FALL AND IMPLICATIONS FOR A DEVICE TO PREVENT INJURIES

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EXECUTIVE SUMMARY

The impetus for this work is the "SOF [Special Operations Forces] Technology Base Project Definition Document for Lower Extremity Assistance for Parachutist (LEAP)." The proposed program aims to develop a device to prevent lower extremity injuries to combat-loaded soldiers who parachute, fast rope, or rappel onto unimproved drop zones. The device should reduce impact forces and moments. It should restrict abnormal bending of the joints, but it should allow normal bending of the joints so that the user can still do a proper parachute landing fall (PLF).

The results of this program show that impact-absorbing material, which can be attached to the bottom of a paratrooper's boots, will reduce the impact forces and moments that occur when he does a PLF. Reducing the impact forces and moments should reduce injuries because large impact forces and moments cause injuries.

To specify the requirements of a device to prevent lower extremity injuries, data were collected about the forces, moments, and displacements to which SOF soldiers are subjected as they perform a PLF. Two experiments were conducted as part of this project; both were conducted in an indoor laboratory where test participants jumped off platforms and performed PLFs. A force plate and high speed video cameras measured the ground reaction forces, ground reaction moments, and displacements of the test participants' lower extremities as they performed their PLFs. Subjective data were collected about equipment and PLF performance via questionnaires.

In the first experiment, conducted from 2 to 26 February 1993, 30 airborne-qualified SOF soldiers jumped from 1.07-m (3.5-ft), 1.37-m (4.5-ft), and 1.71-m (5.6-ft) platforms. Jumps from these heights resulted in descent velocities at impact of approximately 4.57 m/s (15 ft/s), 5.18 m/s (17 ft/s), and 5.79 m/s (19 ft/s), respectively. These descent velocities are within the range of descent velocities of the Army T-10B and MC1-1B parachutes. This first experiment was used to collect baseline biomechanical data about PLFs and to evaluate commercially available braces (ankle braces and knee braces) and a viscoelastic impact-absorbing material as a means of reducing the effects of the landing impact.

The results of this experiment show that the viscoelastic material reduced the forces and moments significantly more than when jumps occurred with boots only or with the commercially available braces. For jumps in the braces, the vertical and horizontal forces are generally greater than for jumps in boots only. The maximum moments for jumps in the braces were lower than the maximum moments for jumps in boots only, but at the times of maximum vertical force and maximum horizontal force, the moments for jumps in the braces were higher than for jumps in boots only.

The viscoelastic material is able to reduce the impact forces and moments because it lengthens the time during which the impact is absorbed. On the other hand, the braces increase forces and moments at times of maximum vertical and horizontal force for one or more of the following reasons: they restrict joint motion, they change the neuromuscular control of the legs, they make test participants feel stiff so they act stiffly when they land, or the test participants get the false sense that the braces themselves will absorb the impact.

One of the most important accomplishments of this experiment is the creation of a data base of quantitative kinetic and kinematic measures of PLFs. These data are available for other researchers investigating the responses of individual bones and ligaments. The data can also be used to validate computer simulations of PLFs.

Based on the results of the first experiment, it is recommended that impact-absorbing material, such as the viscoelastic material, be used in a device to prevent injuries. Because the forces and moments that cause injuries to paratroopers start at the point of contact and are transmitted up the body, the impact-absorbing material should be on or in the soles of the paratroopers' boots.

In the second experiment, conducted from 21 September to 22 October 1993, 24 different airborne-qualified SOF soldiers jumped from 1.37-m (4.5-ft) and 1.71-m (5.6-ft) platforms. The soldiers tested impact-absorbing soles made from four different materials.

The results of the experiment showed significantly lower forces and moments for jumps with the impact-absorbing soles than occurred in jumps in boots only or jumps with ankle braces. Among the impact-absorbing soles, the differences in forces and moments were not statistically significant.

During this experiment, the ankle brace used in the first experiment was worn with the impact-absorbing soles. A device that combines an ankle brace and impact-absorbing soles should be able to reduce injuries because it has the ankle brace for stability and the impact-absorbing sole for force and moment reduction.

Improvements suggested for the prototypes tested in this experiment are (a) integrate the sole and ankle brace into one unit; (b) allow more normal extension of the ankle than the jump brace permits; and (c) optimize the soles for thickness, weight, impact-absorbing properties, and ease of movement during such activities as walking and running. The design of such a device must also include the top four design features identified through the questionnaires in both experiments. It must be adjustable, portable and lightweight, foot cushioning, and easy to don and doff. The ideal impact-absorbing sole and ankle brace unit would protect the ankle from injuries attributable to twisting, allow normal extension of the ankle joint, be less than 3.81 cm (1.5 in.) thick, weigh less than 1.14 kg (2.51 lb) per pair, reduce vertical impact forces by 20% or more, reduce horizontal impact forces by 10% or more, and allow soldiers to walk and run short distances (less than 1 km [0.6 mi]) without significantly changing their gait.

For the future, knee and hip protection, which allows a normal range of motion and acts like a splint but does not bind the legs tightly, should be developed. Integration of knee and hip protection into a device that absorbs impact and supports the ankle will then provide a complete lower extremity protective device.

LOWER EXTREMITY ASSISTANCE FOR PARACHUTIST (LEAP) PROGRAM: QUANTIFICATION OF THE BIOMECHANICS OF THE PARACHUTE LANDING FALL AND IMPLICATIONS FOR A DEVICE TO PREVENT INJURIES

INTRODUCTION

The Need

The impetus for this work is the "SOF [Special Operations Forces] Technology Base Project Definition Document For Lower Extremity Assistance For Parachutist (LEAP)." The project definition document is a response to an operational safety need. The program proposed in the document aims to prevent sprains and fractures of the lower extremities (feet, ankles, legs, knees, thighs, and hips) of combat-loaded soldiers during parachute landings, fast rope insertions, and rappelling from low altitude aircraft. The document suggests using lightweight, high strength materials and force-attenuation devices in a reusable, brace-type device.

The development of a device to prevent lower extremity injuries is aimed at increasing the survivability of SOF soldiers. These soldiers risk injury because they often carry more than 45 kg (100 lb) of equipment as they parachute, fast rope, or rappel onto unimproved drop zones. The risk of injury is further increased because these missions are often performed during bad weather and darkness. The desire for lower altitude, higher speed parachute drops in the future is another potential factor affecting survivability. Soldiers parachuting from lower altitudes and at higher speeds are likely to land at higher speeds, and they will probably have less control over their orientation with respect to the ground.

The Parachute Landing Fall (PLF) Technique

The landing technique taught to parachutists in the Army is the parachute landing fall. The idea behind the PLF is to reduce impact forces and injuries by distributing the impact over a large area of the body and by increasing the time during which the impact is absorbed. Automobile air bags use this same principle for injury prevention. Field Manual 57-220, Basic Parachuting Techniques and Training (Department of the Army and Department of the Air Force, 1984) describes the PLF and the five points of contact that the parachutist's body makes with the ground. Figure 1 shows the PLF; the sequence for the five points of contact is (a) balls of the feet, (b) calf, (c) thigh, (d) buttocks, and (e) latissimus dorsi muscle.

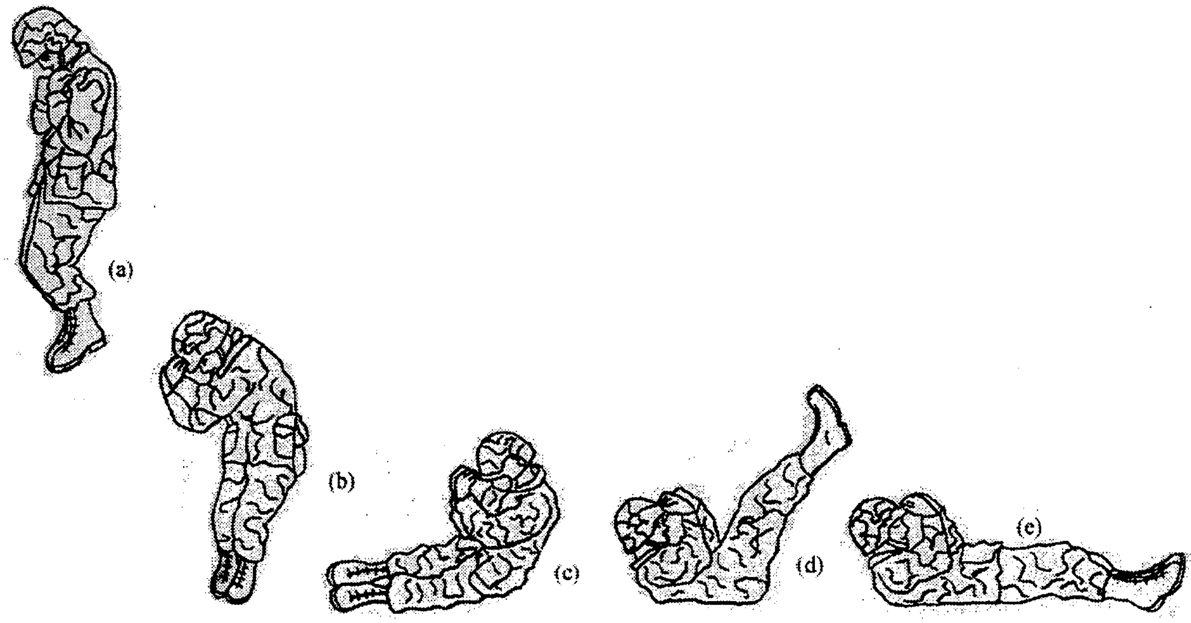

Figure 1. The parachute landing fall sequence: (a) preparing to land; (b) balls of the feet (toe touchdown); (c) calf, thigh, and buttock impact; (d) rolling across latissimus dorsi muscle; (e) end.

Parachuting Injuries

In parachuting, most injuries occur during landing (Ciccone & Richman, 1948; Essex-Lopresti, 1946; Hallel & Naggan, 1975; Kirby, 1974; Neel, 1951). Most of the injuries involve the lower extremities. Studies by the authors previously mentioned report that lower extremity injuries account for 32% to 86% of parachuting injuries, depending upon the study cited. Of the lower extremity injuries, 32% to 75% are ankle injuries, depending upon the study cited. Injuries to other parts of the body are reported at 4% to 39% for the pelvis and spine, 3% to 17% for the upper extremities, and 0% to 21% for the head and neck, again depending upon the study cited.

The mechanisms for various parachuting injuries are presented by Ciccone and Richman (1948), Essex-Lopresti (1946), and Neel (1951). Mechanisms causing the most common injuries are summarized by Ciccone and Richman's four classifications:

1. Torsion plus landing thrust.

2. Backward landing.

3. Opening shock.

4. Violent vertical landing.

Torsion plus landing thrust is the most common lower extremity injury mechanism. It is the result of vertical and horizontal impact forces combined with torsional stresses which can cause numerous injuries such as ankle sprains and leg fractures (see Figure 2). In a backward landing (see Figure 3), the paratrooper's buttocks and head impact the ground. This can cause compression fractures of the vertebrae and head injuries. The opening shock mechanism (see Figure 4) includes whiplash and suspension line entanglements that occur as the parachute opens. When upper or lower extremities become entangled in the suspension lines, ligaments and muscles can be ruptured or stripped from the bone, and bones can be broken. Violent vertical landings, the fourth injury mechanism, result from excessive vertical impact forces. Multiple fractures of the leg and spine are common for this injury mechanism, which is shown in Figure 5.

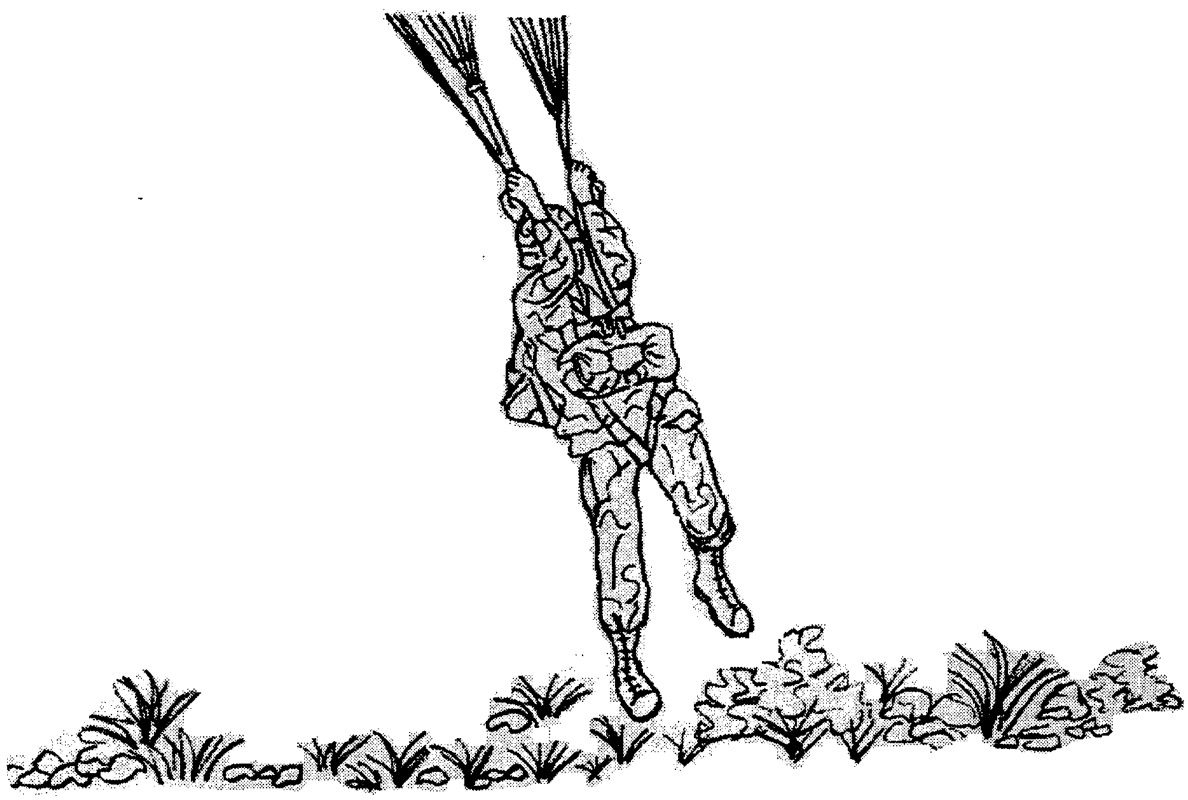

Figure 2. Torsion plus landing thrust injury mechanism.

Figure 3. Backward landing injury mechanism.

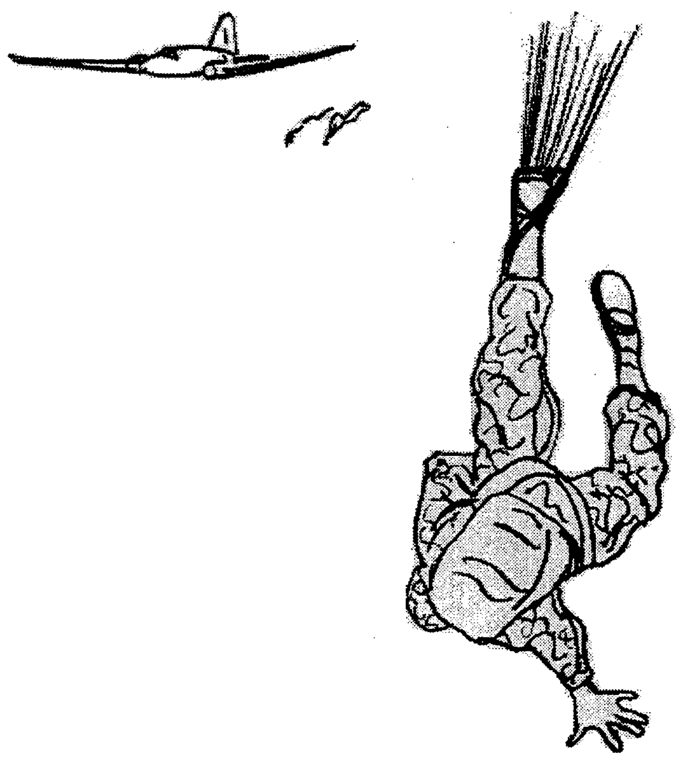

Figure 4. Opening shock injury mechanism.

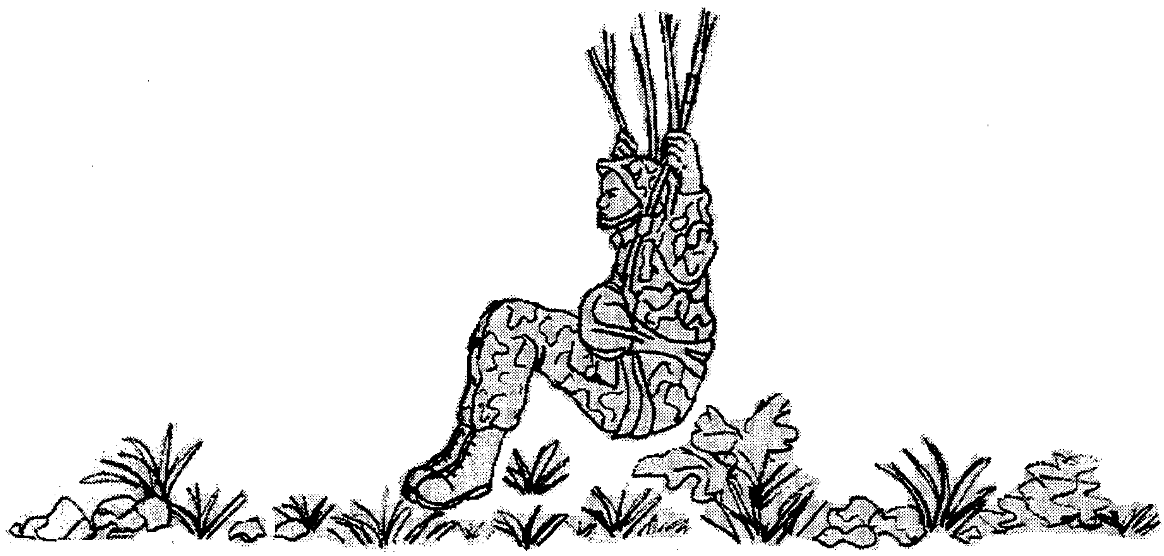

Figure 5. Violent vertical landing injury mechanism.

The overall injury rate for military parachuting during training is approximately 0.35% to 2.1%. These percentages come from studies based on thousands of jumps. Ciccone and Richman (1948) saw more than 3,000 parachutists injured during a period when more than 600,000 parachute jumps were made. The injury rate calculated from their figures is 0.5%. Essex-Lopresti (1946) reported a casualty rate of 2.1% for a period during which 20,777 parachute jumps took place. Neel (1951) reported parachuting injuries from 1946 through 1949. For the 174,220 parachute jumps that took place during that time, the injury rate was 0.58%. Hallel and Naggan (1975) examined data from 83,718 parachute jumps and found the overall injury rate to be 0.626%. Pirson and Verbiest (1985) examined records of 201,977 parachute jumps that occurred over a 10-year period. The injury rate was 0.5%. Pirson and Pirlot (1990) examined data from 15,043 parachute jumps. They found the injury rate to be 0.35%. Amoroso et al. (1994) collected data about 3,674 parachute jumps. Approximately half of the soldiers wore an ankle brace during their jumps. The overall injury rate for all the soldiers in the study was 1%.

The injury rate for parachute jumps made during combat is difficult to calculate because the exact number of jumpers and the causes of all the injuries usually are not known. A recent instance of parachuting injuries occurring during combat happened in December 1989. During the first hours of the invasion of Panama, more than 3,300 soldiers from the 82nd Airborne Division and XVIII Airborne Corps parachuted into Panama. More than 1,700 SOF soldiers also parachuted into Panama during the assault (Steele, 1990). It is estimated that during the first day of the invasion, 54% of the 150 casualties evacuated had jump-related injuries (81 casualties from parachuting) (Office of the Surgeon General and the Walter Reed Army Medical Center-Center of Excellence in Military Medical Research and Education, 1990). Therefore, the injury rate for parachuting during the Panama invasion can be estimated at 1.6%.

Many factors affect the injury rate for parachuting. The main factor appears to be poor technique by the parachutist (Essex-Lopresti, 1946; Neel, 1951). Other factors are parachute descent rate, wind speed, landing terrain, darkness, and the parachutist's weight. The injury rate is higher for parachutes with a faster descent rate. For jumps from a plane using a parachute with a descent rate of 6.7 m/s (22 ft/s), the injury rate was 0.19%, and for similar jumps using a parachute with a descent rate of 5.6 m/s (18.4 ft/s), the injury rate was 0.053% (Pirson & Verbiest, 1985). As wind speed increases, the injury rate increases. Essex-Lopresti (1946) found an injury rate of 1% for wind speeds as great as 13 knots (15 mph) and an injury rate of 2.5% for wind speeds of 13.9 to 17.4 knots (16 to 20 mph). Pirson and Verbiest (1985) found an injury rate of 0.2% at wind speeds of 4 knots (4.6 mph) compared to an injury rate of 0.9% at wind speeds of 16 knots (18.4 mph). The injury rate for landings on rough terrain (1.8%) is higher than the injury rate for landings on sand dunes (0.57%) (Hallel & Naggan, 1975). Night jumps have a higher injury rate than day jumps (0.336% versus 0.18% [Hallel & Naggan, 1975] and 0.7% versus 0.17% [Pirson & Verbiest, 1985]). The injury rate is higher for heavy parachutists than for lightweight parachutists. Essex-Lopresti (1946) found an injury rate of 0.22% for heavy parachutists compared to an injury rate of 0.01% for lightweight parachutists, and Pirson and Pirlot (1990) found an injury rate of 0.622% for heavy parachutists compared to an injury rate of 0.304% for lightweight parachutists.

Previous Studies

Most of the previous studies about landings have been done with gymnasts and recreational athletes. These studies report maximum vertical and or horizontal impact forces for a variety of conditions. Özgüven and Berme (1988) measured the impact forces of gymnasts when they landed after dismounting the horizontal bar. The maximum vertical force they recorded ranged from 8.2 to 11.6 times body weight. A study by McNitt-Gray (1991) examined vertical and horizontal impact forces for jumps from 0.32 m, 0.72 m, and 1.28 m. The average maximum vertical impact forces for gymnasts were 3.93, 6.26, and 10.96 times body weight for jumps from the lowest to highest heights. For the recreational athletes, the average maximum vertical impact forces were 4.16, 6.38, and 9.12 times body weight for jumps from the lowest to highest heights. The maximum horizontal impact forces were approximately 0.5, 1.0, and 2.0 times body weight for jumps from the lowest to highest heights. Mizrahi and Susak (1982) had subjects drop from 1 m, land on the balls of their feet, and then naturally absorb the impact. For these landings, the maximum vertical force ranged from 6.6 to 10 times body weight. When they had subjects land flat-footed and then roll to absorb the impact, the maximum vertical forces were 6.1 to 9 times body weight. The study by Dufek and Bates (1990) examined maximum vertical forces for a combination of conditions: jump height, jump distance, and technique. They found that vertical forces generally increased with increasing jump height and knee stiffness. In a study of vertical jumping and landing, Lees (1981) reported maximum vertical impact forces for "hard" and "soft" landing styles of approximately 3.5 and 2 times body weight, respectively.

Very few studies have been conducted to examine impact forces on military parachutists landing from a jump. Reid, Doerr, Doshier, and Ellerston (1971), in a study for the Navy, used linear accelerometers on parachutists to measure the acceleration of opening shock and landing. The average $+g_Z$ (acceleration in the vertical direction) reported for landings was 7.9 g with a range from 3.2 to 17.0 g. The average $\pm g_X$ (acceleration in the horizontal direction, forward and backward) for landings was 5.8 g with a range from 2.0 to 13.0 g. Most of the parachutists in this study did stand-up landings rather than PLFs.

In a study by Johanson and Wittendorfer (1985), a parachutist was instrumented with triaxial accelerometers. They reported significant differences between parachute landing falls versus stand-up landings, landings in sand versus landings on concrete, landings from 0.61-m (2-ft) platforms versus 1.22-m (4-ft) platforms, and accelerations measured at the thigh versus accelerations measured at the shin.

Unpublished studies by Stannard, Harris, Ward, and Bucknell (1991a, 1991b) examined energy absorption during PLFs from a 1.91-m (6.25-ft) high platform. In both studies, pressure-sensitive film was used to collect information about pressure distribution over the soles of the feet. Their results show that experience has an effect on energy absorption, footgear has an effect on forefoot and heel pressure, and landing position (left or right, front side, or rear) has no effect on energy absorption.

Expert Study Committee

In May 1991, an expert study group was formed to examine parachuting injuries; provide direction to the research conducted in this project; make recommendations about the design and function of a device to prevent lower extremity injuries; and exchange research results, information, and ideas related to preventing parachuting injuries. Members of the committee included the Director of the Center of Excellence in Military Medical Research and Education; orthopaedic surgeons from Walter Reed Army Medical Center (WRAMC); other physicians from WRAMC with parachuting experience; a representative of the Medical Research and Development Command; representatives from the John F. Kennedy Special Warfare Center and School; and researchers from the Human Engineering Laboratory (now the Human Research & Engineering Directorate of the U.S. Army Research Laboratory [ARL]), Harry Diamond Laboratories (now part of ARL), the Material Technology Laboratory, Natick Research, Development, and Engineering Center, Walter Reed Army Institute of Research, U.S. Army Research Institute of Environmental Medicine, and Brooke Army Medical Center.

The expert study group met twice. At the first meeting, in May 1991, the discussions centered around parachuting injuries, parachuting injury research, and potential solutions. The consensus of the group was that a baseline study of the biomechanics of the PLF is required, a review of medical records and literature related to paratrooper injuries is required, and that ankle and knee protection, if necessary, could probably be achieved fairly easily. The second meeting of the expert study group took place in October 1991. Presentations of related research were made and discussed, the jump conditions for SOF soldiers were discussed, the anatomy of the lower extremities was reviewed, information about paratrooper injuries was reviewed, and the scope and general direction of the research to be conducted in the LEAP program were defined.

OBJECTIVE

Immediate Objective

With guidance from the "SOF Technology Base Project Definition Document for Lower Extremity Assistance for Parachutist (LEAP)" and the expert study group, the immediate objective was defined as collecting baseline data about the biomechanics of the PLF and evaluating the efficacy of off-the-shelf braces.

Long-Term Objective

The long-term objective for the data collected in this project is to use them to design and develop a device to prevent lower extremity injuries. Another part of the long-term objective is to use the data for modeling the PLF in conditions that are difficult or impractical to simulate in the laboratory.

PROJECT PLAN

As part of this project, two experiments were conducted. In Experiment I, baseline data were collected to characterize the PLF and to evaluate commercially available braces and a force-attenuating material. The hypotheses of this experiment were

1. There will be no difference in the results as a function of jump height.

2. There will be no difference between the results for jumps with attenuating or bracing devices and the results for jumps with boots only.

3. There will be no relationship between the test participant's weight, stature, or leg length and the biomechanical variables measured.

Different impact-absorbing soles were evaluated in Experiment II. The hypothesis of this experiment was that there will be no difference in the results for jumps from the same height as a function of the cushioning material attached to the test participants' boots.

EXPERIMENT I

Method

Experimental Design

A repeated measures (within subjects) design was used for the experiment. Thirty test participants took part in this experiment, which was conducted from 2 to 26 February 1993. The legwear and jump heights are shown in the test matrix (see Table 1). Each test participant jumped in each legwear from each height. The treatment order was randomized to minimize order effects. Each test participant made 15 jumps. All the test participants performed right front PLFs. The data were collected during two sessions. Test participants made five to ten jumps per session, depending upon travel and testing schedules.

Table 1

Test Matrix Experiment I

Test participants per jump height

Legwear condition	Jump height 1.07 m (3.5 ft.)	 1.37 m (4.5 ft.)	 1.71 m (5.6 ft.)
Boots	30	30	30
Boots and ankle braces	30	30	30
Boots and knee braces	30	30	30
Boots, ankle braces, and knee braces	30	30	30
Boots and viscoelastic material	30	30	30

Jumps from 1.07 m (3.5 ft), 1.37 m (4.5 ft), and 1.71 m (5.6 ft) resulted in descent velocities at impact of approximately 4.57, 5.18, and 5.79 m/s (15, 17, and 19 ft/sec). These descent velocities are within the descent velocities of the Army T-10B and MC1-1B parachutes. Table 2 shows the descent velocities given in Field Manual 57-220 Basic Parachuting Techniques and Training (Department of the Army and Department of the Air Force, 1984).

Table 2

Parachute Rates of Descent

Load in Kg (pounds)	Rate of descent in meters per second (feet per second)		
	Average	Minimum	Maximum
90.9 (200)	5.41 (17.75)	4.69 (15.37)	6.73 (22.06)
102 (225)	5.49 (18.00)	4.77 (15.63)	6.85 (22.48)
114 (250)	5.58 (18.30)	4.82 (15.80)	6.92 (22.70)

Rates of descent depend on air density, air currents, and total load. This table shows the approximate rates of descent for various loads when the T-10B and MC-1B parachutes were used.

Test Participants

The test participants in this experiment were active duty SOF soldiers or soldiers going through the SOF Qualification Course. All the test participants were airborne qualified males on jump status. No one on medical profile was allowed to participate. Each test participant's medical history was reviewed by an Army doctor before he was allowed to participate. The Human Use and Experimental Design Panel of the U.S. Army Research Laboratory (ARL) approved the protocol for the experiment. Before taking part, test participants received a full explanation of the experiment. Each test participant read and signed a volunteer consent agreement.

Apparatus

This experiment was conducted in an indoor laboratory (see Figure 6). To simulate landings from a parachute jump, test participants jumped from platforms and performed PLFs on a padded force plate surrounded by gymnastic mats. All the equipment used in the experiment is now described in detail.

Jump Platform - A wooden platform 1.07 m (3.5 ft) above the landing surface was used for the jumps. Movable steps 0.30 m and 0.64 m (1.0 and 2.1 ft) high were placed on top the platform. As necessary, the steps were moved to the edge of the platform and secured so that the test participants could jump from the required heights. The front of the platform was padded to prevent injury if a test participant were to roll into it. The platform has a safety railing around the top and along the stairs. For added safety, a non-skid surface was attached to the stair treads and to the area from which test participants jumped.

Force Plate - A custom 1.22-m (4-ft) square force plate (Advanced Mechanical Technology, Inc., Newton, Massachusetts) was used in this experiment. The force plate uses strain gauge sensors to measure vertical and horizontal ground reaction forces and moments (torques) about the vertical axis. The signals from the strain gauges pass through an amplifier and into a personal computer where they are collected. The force plate capacity is approximately 17,800 N (4,000 lb) in the vertical direction and 8,900 N (2,000 lb) in the horizontal plane. The data collection rate is 1,000 Hz.

Padding - To simulate landing on a grassy drop zone, the entire force plate was covered with padding. The padding consisted of a 1.27-cm (0.5-in.) thick sheet of medium grade closed cell neoprene sponge topped with a 0.64-cm (0.25-in.) thick sheet of tan, pure, gum latex rated at 40 durometer.

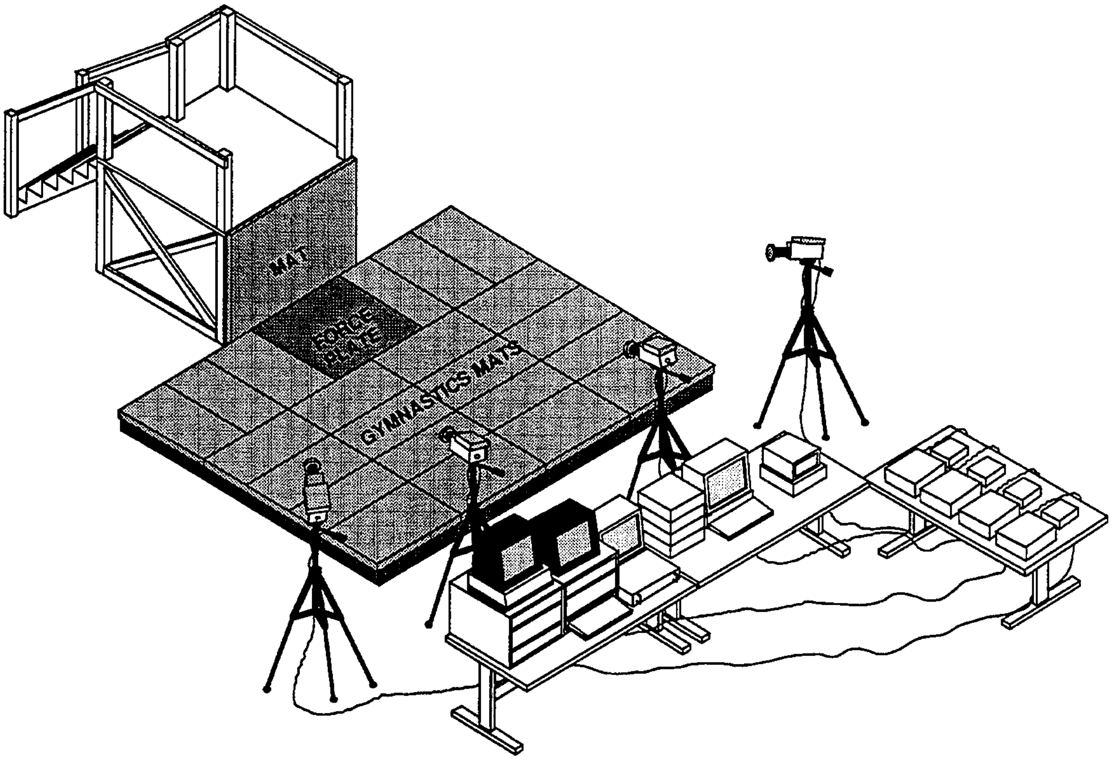

Figure 6. Equipment setup.

Mat Platform - A wooden platform approximately the same height as the force plate was built to provide test participants with a roll-out area for their PLFs.

Mats - Gymnastic mats (Golden Achiever, the Mat King, East Patchogue, New York) were placed on the mat platform to cushion the test participants' rolls at the end of their PLFs. A thick landing mat (Model SLM 600, Oshkosh Tent & Awning Company, Inc., Oshkosh, Wisconsin) was placed in front of the jump platform to prevent test participants from rolling into it.

Motion-Measuring System - A video-based system (Motion Analysis Corporation, Santa Rosa, California) was used to collect data about the displacements of the test participants' lower extremities. The system includes reflective markers, a calibration cube, 200-Hz video cameras with light-emitting diode (LED) stroboscope lights and No. 25 red filters, 200-Hz video recorders (NAC, Burbank, California), a video monitor (Panasonic, Secaucus, New Jersey), a video player (Panasonic, Secaucus, New Jersey), a video processor, special software (ExpertVision™ 3-D and KinTrak), a synchronization box, and a control computer

(SPARCstation™ inter-process communication [IPC], Sun Microsystems, Inc., Mountain View, California).

Reflective Markers - Two types of reflective markers were used. The first type, supplied by Motion Analysis Corporation, consisted of hard plastic spheres, 2.54 cm (1 in.) in diameter, covered with reflective tape and attached to a thin plastic disk. The second type, developed by the Human Research and Engineering Directorate (HRED) of ARL, consisted of soft foam spheres, hemispheres, and sections of spheres covered with reflective paint. The paint used was Scotchlite™ reflective liquid 7210 (3M, St. Paul, Minnesota). The foam spheres and hemispheres were 4.76 cm (1.875 in.) in diameter, and the foam sections were approximately 3.81 cm (1.5 in.) in diameter. A square piece of hook-side Velcro® (Velcro USA, Inc., Manchester, New Hampshire) was attached to the markers. This allowed the markers to be attached to elastic bandages wrapped around test participants' legs.

ExpertVision - The software package ExpertVision 3-D was used for three-dimensional motion analysis. The software has utilities for video calibration, synchronized force and video data acquisition, and video processing. The video calibration determines the relationship between the real world and the video coordinates for each camera position. The force and video data collection is centrally controlled and synchronized to provide time-matched samples. The video processing functions include video digitizing, identifying and sorting the targets in all camera views, resolving merged and hidden targets, and tracking targets through time to determine the three-dimensional trajectories for each target.

KinTrak - The biomechanical analysis software package KinTrak was used to integrate the force and motion data supplied by ExpertVision 3-D. KinTrak converts the raw kinetic data collected from the force plate into forces, moments, and centers of pressure for each trial. KinTrak also takes the kinematic data (the x, y, and z coordinates of the video markers) and calculates displacements, angles, velocities, and accelerations in three dimensions. The kinetic and kinematic data can also be used to calculate joint forces and moments using inverse dynamics.

Ankle Braces - Ankle braces were used in some of the test cells to see if they change the displacements, forces, or moments significantly. The jump brace (02G) (Aircast, Inc., Summit, New Jersey) was used in this experiment (see Figure 7). It is designed for paratroopers, and it is worn on the outside of the boot. The brace is designed to allow nearly normal flexion and extension while limiting inversion. The jump brace was chosen because it is the only ankle brace designed for paratroopers and because it is being used in an ongoing study. The U.S. Army

Research Institute of Environmental Medicine is studying the effect of the jump brace on the incidence of ankle and other injuries associated with military parachuting.

Figure 7. Ankle braces.

Knee Braces - In some of the test cells, knee braces were worn to see if they significantly change the displacements, forces, or moments that the test participants experience. Based on the recommendation of orthopaedic surgeons at Womack Army Medical Center, Ft. Bragg, North Carolina, the combined instabilities (CI) brace (DonJoy, Carlsbad, California) was chosen for this experiment. The CI brace is designed to allow flexion and extension while controlling medial-lateral and anterior-posterior motions (see Figure 8).

Figure 8. Knee braces.

Viscoelastic Material - A viscoelastic material, Sorbothane® (Sorbothane, Inc., Kent, Ohio), was placed on top of the padded force plate for some of the test cells. The material was recommended by the Materials Directorate of ARL to see if it attenuates the impact forces and moments. The Sorbothane was 3.81 cm (1.5 in.) thick, with a durometer rating of 30.

Anthropometric Instruments - For anthropometric measurements and marker measurements, the following instruments were used: standard anthropometers, special long, 40-cm (15.75-in.) anthropometer blades, special short anthropometers constructed from sliding calipers, a Holtain caliper, a standard sliding caliper, and a standard spreading caliper.

Measuring Box - A specially designed wood structure was constructed in which test participants stood while either joint location measurements or marker measurements were taken. It consisted of a rigid box floor to which was attached a vertical back wall and a vertical left wall (test participant's left) (see Figure 9). This structure was built of 1.91-cm (3/4-in.) plywood specially selected for flatness and absence of surface flaws. It was constructed to provide three orthogonal surfaces to serve as a Cartesian reference frame. The origin of the reference frame is the intersection of the three surfaces. The intersection of the back wall and the floor defines the x-axis; the intersection of the left wall and the floor defines the y-axis; and the intersection of the back wall and the left wall defines the z-axis. The box attached to the left wall at hip level and a 5-cm-thick block placed on the floor against the back wall were used to position test participants.

Practice Equipment - A jump platform, mat platforms, and mats were provided for test participants to practice their PLFs before data collection began. The practice jump platform was 1.22 m (4 ft) above the mat surface. The mat platforms and mats were the same as those described earlier. A mat was placed in front of the practice platform to prevent test participants from accidentally rolling into the platform.

Boots and Uniforms - Each test participant wore his own hot weather boots. Hot weather boots are commonly referred to as jungle boots. Test participants wore their physical training uniforms (shorts and T-shirts) with their boots.

Protective Helmets - For head protection, test participants wore lightweight bicycling helmets (Bike Nashbar, Youngstown, OH) during their jumps. The helmets meet American National Standards Institute (ANSI) Z90.4 and SNELL B90 standards.

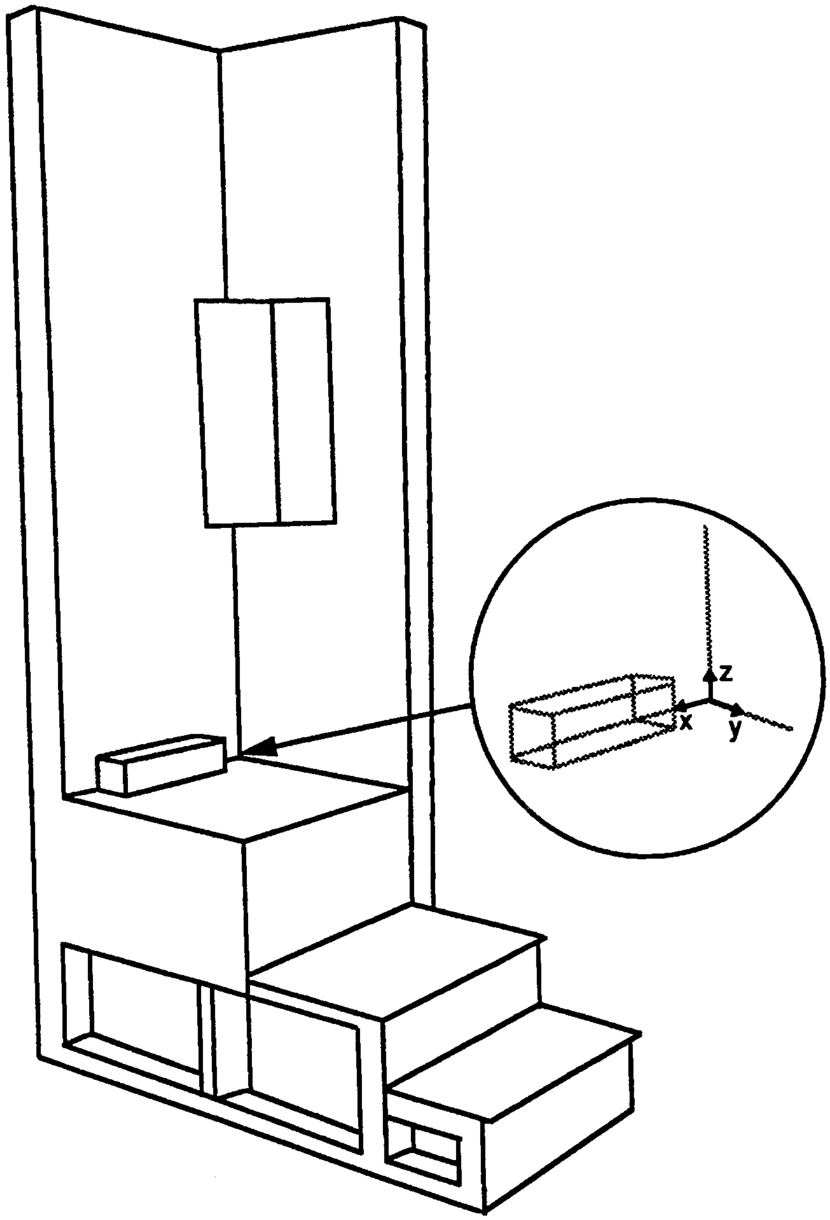

Figure 9. Measuring box.

Elbow Pads - For safety reasons, test participants wore elbow pads (Adams USA, Inc., Cookeville, Tennessee) during their jumps.

Procedure

Warm-Up

At the beginning of each session, test participants did calisthenics and stretching exercises to warm up. Then, they each performed at least three practice PLFs from the practice platform. Practice jumps are part of the standard preparation these soldiers go through before any parachute jump.

Anthropometry

For this experiment, two types of anthropometric measurements were made. First, standard anthropometric measurements were made to ensure that the test participants in this experiment were representative of the Army population. Second, joint center measurements were taken for input to the KinTrak software.

Appropriate anthropometric landmarks were selected from those used in the "1988 Anthropometric Survey of U.S. Army Personnel." These were located by palpation and marked on the test participant's skin as necessary. The measurements made are listed on the data sheet in Appendix A. Stature, weight and cervicale height were measured first. Then the measurements needed to locate the joint centers were taken. Some of these measurements were taken with the test participants in the measuring box.

To achieve the most accurate and consistent relationship between joint center measurements (taken once for each test participant) and marker measurements (taken for each jump), test participants' posture in the measuring box was standardized. The test participant was instructed to stand erect, ease to the left until his hip just touched the hip-positioning block, ease backward until his heels just touched the heel-positioning block, and then lean back until his shoulders and buttocks just touched the back wall.

Measurements of the x, y, and z coordinates of each joint center were made from a landmark to the appropriate measuring box surface. Measurements were made using standard anthropometers provided with base plates to ensure that all measurements were made normal to the measuring box surface. Some measurements, particularly foot measurements, were made with the special short anthropometer. Measurements were also made to provide correction factors to account for the effects of boots and ankle braces. The joint centers are defined as shown in Table 3.

Fitting the Braces

The knee braces, which are available in five sizes, were fit according to the manufacturer's instructions. The ankle braces and knee braces were put on the test participants according to the manufacturer's directions. To ensure that the proper size braces were worn correctly, members of the team conducting the experiment always put the braces on the test participants.

Table 3

Joint Centers

Joint	Coordinate	Definition
Ankle	X	Lateral malleolus to side wall minus one half bimalleolar breadth
	Y	Lateral malleolus to back wall
	Z	Lateral malleolus height
Knee	X	Lateral femoral epicondyle to side wall minus one half bicondylar breadth
	Y	Lateral femoral epicondyle to back wall
	Z	Lateral femoral epicondyle height
Hip	X	Same as knee X coordinate
	Y	Trochanter to back wall
	Z	Trochanteric height

Placing the Markers

The reflective markers used to track the motions of the test participant's right leg were attached to his thigh, lower leg, and foot. Specifying the motion of each segment of the leg in three-dimensional space required three markers on each segment (see Figure 10). For practical reasons, the foot was treated as a rigid body, ignoring tarsal, metatarsal, and digital articulations. The locations for the markers were chosen to provide optimum viewing by the video cameras. Except for Marker 8, all the markers were attached to elastic bandages wrapped around the test participant's thigh, lower leg, and foot. Marker 8 was attached to a square piece of loop-side velcro placed on the boot. Markers 6 and 7 were the hard plastic type because of their small size and good contrast on the video tape. All the other markers were the foam type. They were used to provide large reflective surfaces and to eliminate the possibility of injury when test participants rolled over them while doing their PLFs. For consistency, markers were always put on the test participants by members of the team conducting the experiment.

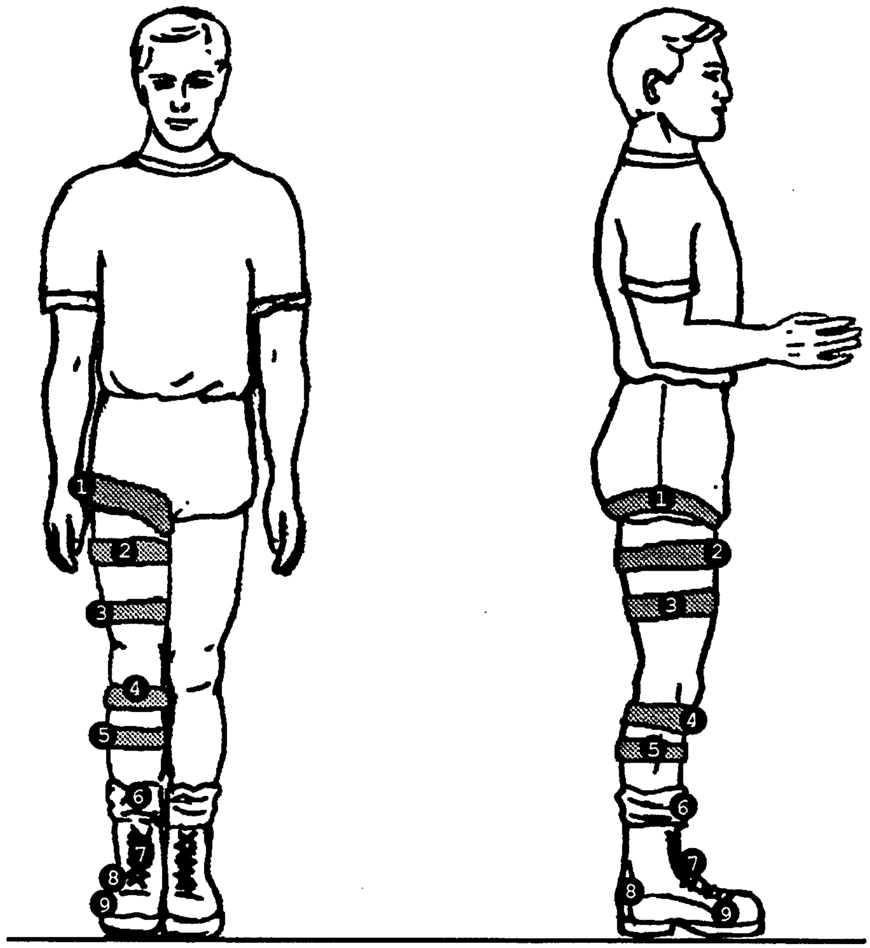

Figure 10. Marker locations.

Measuring the Marker Locations

Test participants were positioned in the measuring box in the manner described in the Anthropometry section. The location of each marker was measured from the floor, the back wall, and the left (side) wall. (See the data collection sheet in Appendix B.) Standard anthropometers and special short anthropometers were used to make the measurements, which were taken to the projected center of each marker.

Data Collection

After the marker locations were measured, the jump platform was prepared for the test participant. The movable steps were positioned to provide the proper jump height. Test participants climbed to the top of the jump platform, moved to the edge above the force plate, and prepared to jump. Upon receiving a signal from the data collector, test participants jumped onto the force plate and performed a PLF.

Force and Moment Data

The forces and moments were measured in three directions by foil strain gauges attached to load cells at each of the four corners of the force plate. The strain gauges formed six Wheatstone bridges. Three of the bridge output voltages were proportional to the forces in the x, y, and z directions. The other three output voltages were proportional to the moments about the x, y, and z axes.

The six output voltages from the force plate were amplified with a gain of 1,000 and filtered by a low pass filter with a cutoff frequency of 1,050 Hz. The forces and moments were sampled at a rate of 1,000 Hz for 3 seconds. The amplified signals were passed through a 12-bit analog-to-digital converter and collected in real time on a 386 personal computer (PC). The data were written in American standard code for information interchange (ASCII) format. The ASCII value corresponded to a digital count in the range from 0 to 4096, which was proportional to the output voltage. Immediately following collection, the data were transferred, via Ethernet connection, to the host workstation for long-term storage and analysis.

Video Data

The three-dimensional displacement information was obtained from high speed video recordings of the test trials. Black-and-white, charge-coupled device (CCD) video cameras and high speed video recorders captured the video data at 200 Hz in video home system (VHS) format. This gave one sample every 5 ms. To determine the three-dimensional position, four cameras approximately 40° apart at a distance of about 7.3 m (24 ft) from the force plate were required to capture the markers throughout the landing event.

The time-space coordinates of the video markers were used to determine positions and joint angles. Because only the marker locations were needed, the rest of the image could be ignored. To separate the markers from the background image, the contrast of the markers was increased by using the LED stroboscope lights and the red filters.

Synchronization

The force and moment data were synchronized with the video recordings using a trigger switch. As a test participant started to jump, a switch was pressed, which simultaneously started the force plate sampling and also placed an audio tone on each of the video recordings. The audio tone was used as a marker to designate the frame on the video tape that corresponded to the start of the force plate data collection. The trial duration was set at 3 seconds. This provided 600 frames of video data and 3,000 samples from the force plate, or one video sample for every fifth force and moment sample.

Subjective Data

After each jump, test participants completed a post-jump questionnaire (see Appendix C). The questionnaire provided subjective feedback about the legwear being tested. For each jump, test participants compared their landing to previous parachute landings (softer, the same, or harder). For jumps with the braces or jumps onto the viscoelastic material, test participants were also asked how easy it was to walk, make the initial landing, and roll.

After test participants completed all their jumps, they completed a post-study questionnaire (see Appendix D). The post-study questionnaire asked test participants to rank the legwear based on comfort, leg support, aid to PLF posture during landing, and preference for use during training or missions. Test participants also rated the necessity of 20 features that a future lower extremity protective device could have, and they answered questions about their PLFs during actual parachute jumps.

Data Processing

Raw Data

The raw force data were loaded directly into the KinTrak biomechanical analysis software. The KinTrak software processed the raw force and moment data from the six channels, converting the electrical units into units of force (Newtons) and moment (Newton-millimeters) using a sensitivity matrix supplied by the force plate manufacturer.

The raw video data required processing by the ExpertVision 3-D software before they could be loaded into KinTrak for analysis. The video recordings were played one at a time, at a slower speed and fed through the video processor to create a digitized version on the host computer. The recorded images contained sufficient contrast so that a gray scale threshold could be set by the video processor, reducing the image to two gray levels. The elements above the threshold (the markers) were white, and the elements below the threshold (the background) were black. The images were digitized by transferring to the host computer the x and y coordinates of the pixels that outline the transitions from white to black.

All four digitized images of each trial were used to determine the x, y, and z coordinates of the markers. Each marker in a trial was manually identified in a particular frame of one camera view. After the software identified all the markers in the other camera views and the identities were confirmed, the markers were tracked frame by frame, through time and space, to obtain three-dimensional trajectories. The time-space coordinates were then loaded into the KinTrak software and combined with the transformation measurements to relate the marker positions to the joint centers.

Trial Data

In KinTrak, the file for each trial contained force, moment, and marker position data, along with the test participant's height and weight. The force and marker data were stored as x, y, and z components. Moment data were available about the z-axis only. These three data sets existed in the KinTrak program as continuous curves collected over the 3-second data capture. Using process-variable definition and data marker creation options in KinTrak, the reactive absorption phase of the PLF, along with distinct events during the PLF, were identified.

After identification of these landing events, the KinTrak software was used to determine the accompanying force, moment, and time values. In addition, the data manipulation options of integration and vector projections were used to calculate vertical impulses and joint angles. The PLF performance measures were then tabulated for each trial. These data tables were transferred into spreadsheets in the statistical analysis software SPSS to allow creation of additional performance variables, along with the calculation of descriptive statistics and analyses of variance.

Results and Discussion

Experimental Analysis

In the two experiments of the LEAP program, data were collected and analyzed to biomechanically characterize the PLF technique and evaluate the injury reduction potential of various legwear items. Kinetic and kinematic data were collected in these experiments. The kinetic data, measured by the force plate, included forces, moments, and impulses. The kinematic data, displacements and velocities, were collected by the video motion-measuring system. Table 4 lists the biomechanical measures collected in the LEAP experiments, along with their analyses' benefits.

Table 4

Biomechanical Measures Used to Characterize PLFs

Biomechanical measures	Analysis information provided
Forces vertical horizontal (landing surface plane)	Impact felt by paratrooper during the PLF
Moments	Twisting forces about the vertical axis
Impulses	Impact forces absorbed over the time of the PLF
Angles Ankle Knee	Ankle and knee joints' bending during the PLF

As mentioned earlier, Ciccone and Richman (1948) identified four injury classifications for parachuting injuries. The focus of the LEAP program, prototype development of an impact attenuation device, addressed two common injury problems: torsion plus landing thrust, and violent vertical landing. These common injury mechanisms are driven by the vertical and horizontal forces, along with torsional stresses experienced by a paratrooper during landing. Because of the contributions of these force and torsion factors toward parachute injuries, the analysis of the LEAP experiments concentrated on evaluating the forces and moments caused by the PLF technique.

Before the force-attenuating legwear was evaluated, the data of the LEAP experiments were used to biomechanically characterize the PLF technique. Similar to the Dufek and Bates (1990) characterization of human landings, the PLF procedure was resolved into certain distinct events: initial contact (C); toe (F1) and heel (F2) touchdowns; the end of reactive absorption (E); knee bend (K); and landing surface contacts of the calves, thighs and buttocks (L). Figure 11 indicates these events on a typical vertical ground reaction force curve.

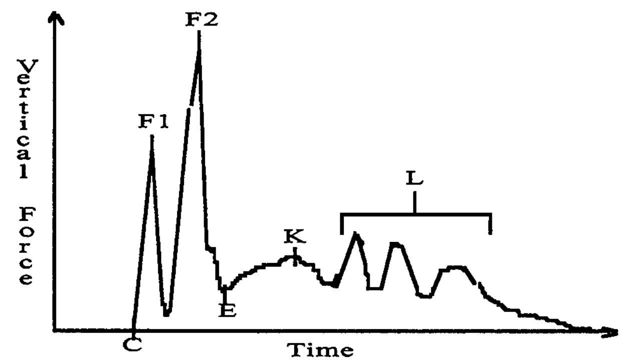

Figure 11. PLF events identified on a typical vertical ground reaction force curve: initial contact (C); toe touchdown (F1); heel touchdown (F2); end of reactive absorption (E); knee bend (K); and lower extremity contact of calf, thigh, and buttock (L).

Preliminary analyses identified these events and established baseline biomechanical measures of forces, moments, impulses, angles, displacements, and velocities. These baseline biomechanical measures were made as soldiers performed PLFs in combat boots for jumps from heights of 1.07 m (3.5 ft), 1.37 m (4.5 ft), and 1.71 m (5.6 ft), respectively. Analyses of the PLF results for baseline characterization and impact attenuation approaches concentrated on the toe and heel touchdowns, the first two major impact events. The paratrooper typically experiences the greatest horizontal and vertical landing forces, as well as large torsional stresses, during these events. Thus, these are important periods with respect to injuries.

For statistical evaluation, the repeated measures approach was used in both LEAP experiments to minimize any individual soldier differences, such as PLF technique, which may affect the PLF performance. (See Tables 1 and 20 for the experiments' test matrices.) Analyses of variance (ANOVAs) were used to examine the main effects of jump height and legwear approaches on the biomechanical measures of PLF performance. A 0.05 criterion level for significance was employed throughout the analyses. The homogeneity of variance assumption for these analyses was confirmed. If this assumption was not met, the Greenhouse-Geiser correction was applied before significance was determined. Post hoc paired comparisons were also made for significant results through Scheffé's Test or Tukey's Honestly Significant Difference (HSD) Test.

In addition, soldier's anthropometric data were collected for the two paratrooper groups used in the LEAP experiments: stature, weight, and various leg measurements (see Appendix A). The percentile distributions for these anthropometric measurements of the test groups were similar to those from the Army's 1988 anthropometric survey (Gordon et al., 1989). Thus, these two experimental groups were representative of the Army's male soldier population.

Subjective data were also collected in the two LEAP experiments. After finishing each landing, soldiers completed post-jump surveys. Hierarchical loglinear analysis was used to analyze the survey ratings. Soldiers also completed surveys at the end of the experiments. These post-study questionnaires included rankings of the various legwear conditions for overall preference, comfort, support, and PLF positioning. The post-study ratings were evaluated with nonparametric statistics: the Friedman Test and Kendall's coefficient of concordance. In addition, design feature preferences were tabulated and reported.

Experiment I

In Experiment I, baseline biomechanical data were collected for 30 paratroopers' PLFs made from heights of 1.07 m (3.5 ft), 1.37 m (4.5 ft), and 1.71 m (5.6 ft), approximating descent velocities of 4.57 m/s (15.0 ft/s), 5.18 m/s (17.0 ft/s), and 5.79 m/s (19.0 ft/s), respectively. As shown in the experimental matrix in Table 1, soldiers made these jumps in five legwear conditions: boots; boots and ankle braces; boots and knee braces; boots, ankle braces, and knee braces; and boots on a viscoelastic material landing surface. The baseline data, collected for landings made with soldiers in the boots only legwear condition, are summarized in Table 5. Twenty-four soldiers' data were available for these biomechanical measurements of PLF performance.

The results allowed biomechanical characterization of the PLF procedure. As suggested by Dufek and Bates (1990) notation of landing events, we designated the initial period of the PLF as the "reactive landing phase" and delineated its various impact events. These events included initial contact (contact); the first impact peak attributable to toe touchdown (F1); the second impact peak attributable to heel touchdown (F2); and the end point of reactive impact absorption (end). During this initial period, the soldier reactively absorbs most of the landing impact via the trained muscle coordination of the PLF technique. The paratrooper then completes the PLF in a more active mode, pushing up onto the toes and then rolling to touch down the calf, thigh, buttock, and upper torso.

The baseline data were also used as benchmarks to evaluate various bracing and force-attenuating legwear approaches: ankle braces, knee braces, ankle and knee braces worn together, and impact-absorbing material. Since most of the paratrooper injuries involved injuries to the lower extremities (Ciccone & Richman, 1948; Essex-Lopresti, 1946; Hallel & Naggan, 1975; Kirby, 1974; Neel, 1951), it is imperative that the legwear approaches lessen the initial impact effects of the PLF. As mentioned earlier, the efficacy of a legwear approach was determined by examining ground reaction impact forces, moments, impulses, joint angles, and absorption times.

Table 5

Experiment I: Overview of Baseline Biomechanical Measures of the PLF
(combat boot landings)

Biomechanical measure	Range of values
Maximum vertical impact force	3674 N - 24353 N
Maximum horizontal impact force	1238 N - 6813 N
Vertical force at toe touchdown	2857 N - 11206 N
Vertical force at heel touchdown	3723 N - 24353 N
Moment at toe touchdown	(-)2891 N*m - (+) 6892 N*m
Moment at heel touchdown	(-)4850 N*m - (+)10861 N*m
Impulse during early impact absorption	209 N*sec - 509 N*sec
Time to toe touchdown	10 msec - 20 msec
Time to heel touchdown (following toe touchdown)	11 msec - 36 msec
Ankle bend to toe touchdown	3° - 14°
Knee bend to toe touchdown	7° - 22°
Ankle bend to heel touchdown	6° - 40°
Knee bend to heel touchdown	9° - 35°

Note. (+) and (-) values for moments denote, respectively, clockwise or counter-clockwise force application.

In Experiment I, we evaluated three null hypotheses about soldier PLF performance: (a) there will be no difference between landing performance results for jumps made from different heights; (b) there will be no differences in landing performance for different bracing and cushioning (legwear) approaches; and (c) soldiers' stature, weight, and leg lengths are not related to performance results. To evaluate the first two hypotheses, each biomechanical measure for the PLF technique was subjected to an ANOVA, with jump height and legwear as within-subjects effects. These results are discussed in later sections.

Stature, Weight, and Leg Length Correlations with PLF Performance

In evaluating the third hypothesis, we examined the correlations between soldiers' stature, weight, and leg length measurements and the biomechanical performance results. Table 6 shows the biomechanical variables with significant Pearson product-moment results for the correlation analyses.

The soldiers' weights were positively correlated with vertical ground reaction forces during the maximum impact event (Fzmax), maximum resultant force event (Fzmxr), toe and heel touchdown events (Fzf1 and Fzf2), and at the end of passive absorption (Fzend). Correlational analysis revealed that increases in soldiers' weights also increased the vertical moment at maximum vertical impact (Mzfzmax) and the vertical moment at the end of reactive absorption (Mzend) (twisting forces) about the vertical axis when soldiers experienced Fzmax and the end of passive absorption. As expected, most impact times (F1time, F2time, F1f2time, F2endtime, and totaltime) and all impulse measurements, vertical force absorption over time, (Impf1, Impf2, Impf1f2, Impf2end) were significantly correlated with the soldiers' weight measurements. Except for the ankle bend measurement between the F1 and F2 impact events (Caaf12) and knee bend to the F1 impact event (Ckaf1), increasing soldier weight increased ankle and knee bend to the end of passive absorption (variables Caaf1, Caaf2, Ckaf2, Ckaf12).

Pearson correlations between stature and the biomechanical measurements revealed highly significant correlations with the measurements of ankle bend, knee bend, impact time, and vertical impulse absorption. Surprisingly, only the vertical forces (Fzmax and Fzmxr) during the maximum vertical and horizontal impact events significantly correlated with stature measurements. An increase in stature produced a proportional increase in these biomechanical results, except for knee bend between contact and F1 impact where soldiers of larger stature typically had less knee bend.

Table 6

Experiment I: Pearson Correlation Coefficients Between Soldiers' Weights, Statures, and Leg Lengths and Selected PLF Biomechanical Variables

	Biomechanical variable	Weight	Stature	Leg length	Sample size[a]
Forces	Fzmax	.24**	.11*	.10	24
	Fzmxr	.20**	.13*	.10	20
	Fzf1	.23**	.05	-.04	22
	Fzf2	.21**	.07	.03	22
	Fzend	.27**	.09	.23**	22
Moments	Mzfzmax	.12*	-.03	-.06	24
	Mzend	.15**	.03	-.02	22
Impulses	Impf1	.36**	.24**	.09	22
	Impf12	.65**	.33**	.19**	22
	Impf2	.67**	.36**	.20**	22
	Impf2end	.71**	.37**	.30**	22
Impact times	Rtime	.10	.14*	.08	20
	F1time	.27**	.21**	.12*	22
	F2time	.31**	.30**	.22**	22
	F12time	.28**	.29**	.23**	22
	F2endtime	.27**	.24**	.18**	22
	Totaltime	.31**	.29**	.21**	22
Ankle bend	Caaf1	.30**	.24**	.05	15
	Caaf12	.11	.33**	.29**	15
	Caaf2	.26**	.32**	.17*	15
Knee bend	Ckaf1	-.17*	-.20**	-.22**	15
	Ckaf12	.40**	.22**	.07	15
	Ckaf2	.31**	.10	.08	15

**α<.01 significance level. *α<.05 significance level.
[a]Sample sizes for correlational analysis also used in later ANOVAs.

The soldiers' leg lengths were determined as the trochanteric height. Paralleling the correlational analysis results with stature measurements, most impact time and impulse measurements were positively correlated. Except for the vertical ground reaction force at the end of passive absorption (Fzend), Pearson product-moments did not indicate significant linear relationships between leg length and the ground reaction forces. Ankle bend after F1 impact, Caaf12 and Caaf2 measurements, postively correlated with leg length. Oppositely, knee bend to

F1 impact (Ckafl) negatively correlated with leg length as soldiers with longer legs experienced less knee bend.

Examination of Jump Height and Legwear Effects on PLF Performance

In the following sections, the ANOVAs for the biomechanical variables' results do not employ weight, stature, and leg length as concomitant variables since a repeated measures design was evaluated. Also, multivariate analyses were not employed because of the distinctiveness of PLF events time-wise and data analyses conventions in previous PLF and landing studies. The ANOVA tables report significance at a levels of .05, .01, or .001. Analyses' sample sizes vary from n=24 to n=15.

Forces

Soldiers' PLF impact forces were considered to be the most important dependent variables for examining performance effects of jump height and attenuating legwear approaches. The occurrence of large vertical forces can cause lower extremity injuries. In the LEAP experiments, we measured the ground reaction forces experienced at the soldiers' feet. The muscles and joints of the paratroopers must ultimately absorb and dissipate these forces when the PLF is performed.

The ground reaction forces were resolved into vertical and horizontal components. We measured vertical ground reaction forces as perpendicular (z axis) to the landing surface of the force plate. Horizontal forces were calculated as the resultant of the forces present in the x and y directions of the landing surface. The vertical and horizontal ground reaction forces included maximum impact forces (Fzmax and Frmax), first impact peak forces (Fzf1 and Frf1), second impact peak forces (Fzf2 and Frf2), and the forces at the end of reactive impact absorption (Fzend and Frend).

The ANOVA results for jump height and legwear effects on ground reaction forces are presented in Table 7.

Table 7

Experiment I: ANOVA Results for Vertical and Horizontal Resultant Forces

Variable	Effect	F-ratio	*p*-value
Fzmax	Jump height	F(2,22)= 85.26	*p*<.001
	Legwear	F(4,20)= 27.18	*p*<.001
	Jump height x legwear	F(8,16)= 2.95	*p*<.05
Frmxz	Jump height	F(2,22)= 12.48	*p*<.001
	Legwear	F(4,20)= 21.51	*p*<.001
	Jump height x legwear	F(8,16)= 3.08	*p*<.05
Frmax	Jump height	F(2,18)= 90.43	*p*<.001
	Legwear	F(4,16)= 39.09	*p*<.001
	Jump height x legwear	F(8,12)= 7.54	*p*<.01
Fzmxr	Jump height	F(2,18)= 11.26	*p*<.01
	Legwear	F(4,16)= 4.70	*p*<.05
	Jump height x legwear	F(8,12)= 1.74	ns
Fzf1	Jump height	F(2,20)=122.72	*p*<.001
	Legwear	F(4,18)= 8.57	*p*<.001
	Jump height x legwear	F(8,14)= 2.20	ns
Frf1	Jump height	F(2,10)= 20.78	*p*<.001
	Legwear	F(4,18)= 39.10	*p*<.001
	Jump height x legwear	F(8,14)= 6.01	*p*<.01
Fzf2	Jump height	F(2,20)= 89.69	*p*<.001
	Legwear	F(4,18)= 29.43	*p*<.001
	Jump height x legwear	F(8,14)= 2.23	ns
Frf2	Jump height	F(2,20)= 18.57	*p*<.001
	Legwear	F(4,18)= 20.46	*p*<.001
	Jump height x legwear	F(8,14)= 4.31	*p*<.01
Fzend	Jump height	F(2,20)= 3.36	ns
	Legwear	F(4,18)= 8.02	*p*<.01
	Jump height x legwear	F(8,14)= 1.03	ns
Frend	Jump height	F(2,20)= 5.15	*p*<.05
	Legwear	F(4,18)= 2.09	ns
	Jump height x legwear	F(8,14)= 0.85	ns

Maximum Vertical Impact (Fzmax)

Because of Ciccone and Richman's (1948) designation of vertical impact forces as important injury mechanisms during paratrooper landings, we first examined the maximum vertical impact force, Fzmax. The maximum vertical force generally occurred at heel touchdown and the second impact peak on the vertical force curve. Similar to earlier findings for gymnasts' landings (Dufek and Bates, 1990; McNitt-Gray, 1991), paratroopers' maximum vertical forces increased significantly for higher jump heights. The accompanying larger impact velocities produced these results. During the reactive landing phase, vertical forces peaked at 7100 N (8.9 times body weight), 10430 N (13.1 times body weight), and 13480 N (17.3 times body weight) for heights of 1.07 m, 1.37 m, and 1.71 m, respectively.

The various legwear conditions also produced significant differences in Fzmax (see Table 7). As evident in Figure 12, soldiers' landings on the viscoelastic surface were significantly softer (8670 N or 10.9 times body weight) than with the other legwear approaches. Surprisingly, wearing ankle and knee braces together caused the largest vertical impact forces (12360 N or 15.5 times body weight). Apparently, this brace combination must interfere with the muscles' ability to absorb impacts during the PLF technique. Figure 12 also indicates that Fzmax results differed because of interactions between jump height and legwear. Wearing knee braces appears to offer vertical impact reduction for landings from greater heights when compared to ankle braces' and combat boots' performance results.

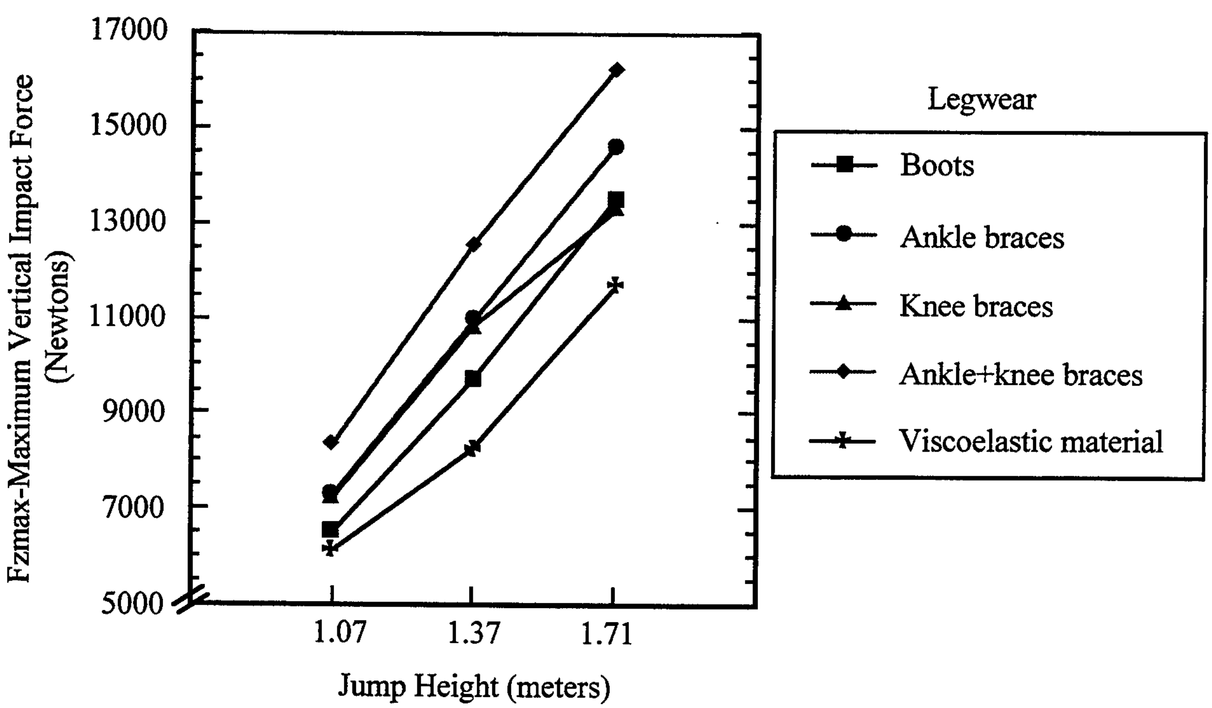

Figure 12. Experiment I: Maximum vertical impact force versus jump height by legwear.

Resultant Force During Maximum Vertical Impact (Frmxz)

At each of the PLF impact events, we always examined the accompanying horizontal resultant force. The horizontal force present during the Fzmax event was designated Frmxz. The Frmxz ANOVA results shown in Table 7 parallel those for Fzmax. Jump height elevation produced significantly larger resultant forces at maximum vertical impact: 1300 N at 1.07 m, 1760 N at 1.37 m, and 1890 N at 1.71 m. Figure 13 indicates a greater increase in Frmxz between the 1.07 m and 1.37 m jump heights.

Again, the viscoelastic material offered significant horizontal force reduction over the other legwear approaches. When compared to landings in boots only, Frmxz was more than 50% smaller on the viscoelastic surface. Post hoc testing revealed many interactions between jump height and legwear conditions: Frmxz results for boots only and viscoelastic landings became more dichotomous with increasing height, and the similarity in Frmxz values when ankle braces were worn alone or with knee braces did not occur at the middle jump height (see Figure 13).

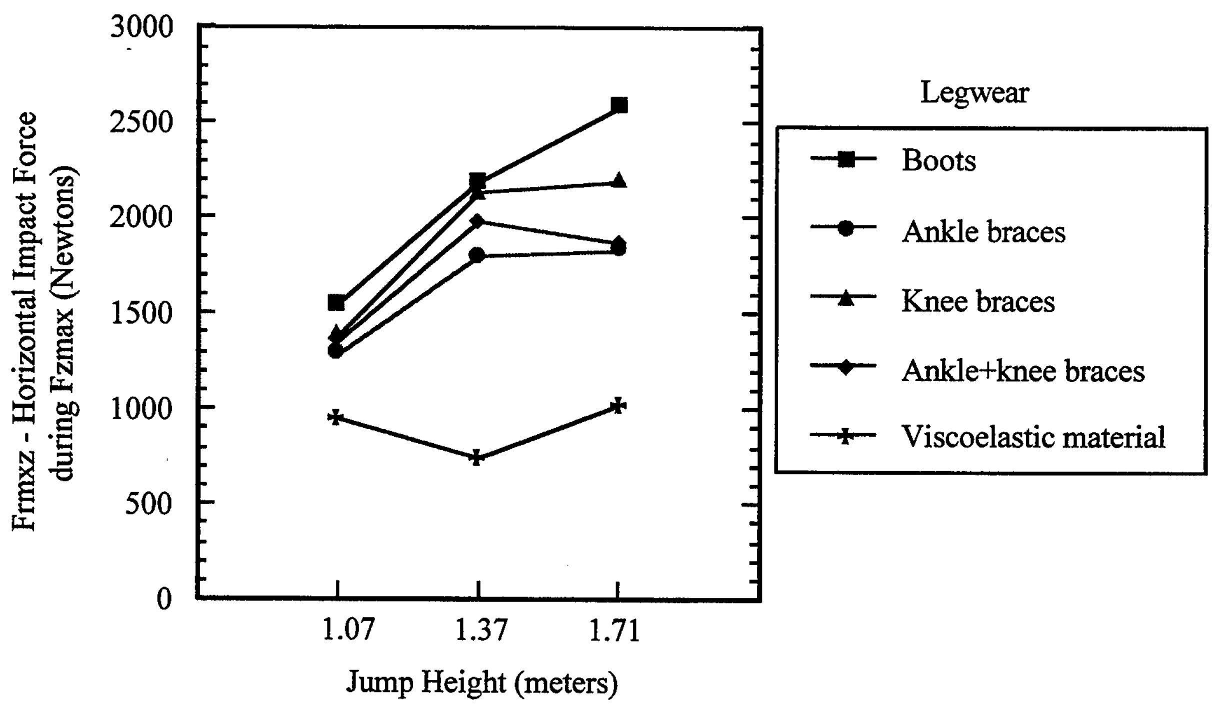

Figure 13. Experiment I: Horizontal impact force at maximum vertical impact versus jump height by legwear.

Maximum Horizontal Impact (Frmax)

In Experiment I, soldiers typically experienced the maximum horizontal impact (Frmax) following toe touchdown, the F1 vertical impact peak. Statistical analyses summarized in Table 7 reveal that jump height, legwear, and their interaction produced significant differences in Frmax results. Varying jump height caused maximum horizontal impact forces of 3140 N to 4430 N or 4.0 to 5.6 times soldiers' body weights. In comparison to the other legwear conditions, only the viscoelastic material approach offered a significant decrease in Frmax. Paratroopers' landings averaged 2520 N on the viscoelastic material, a 1500-N to 1700-N reduction over the other legwear. As seen in Figure 14, soldiers' landings with knee braces had the greater Frmax measurements at 1.07 m and 1.71 m jump heights and the lower results at 1.37 m. This variation in performance drove the interaction effects listed in Table 7.

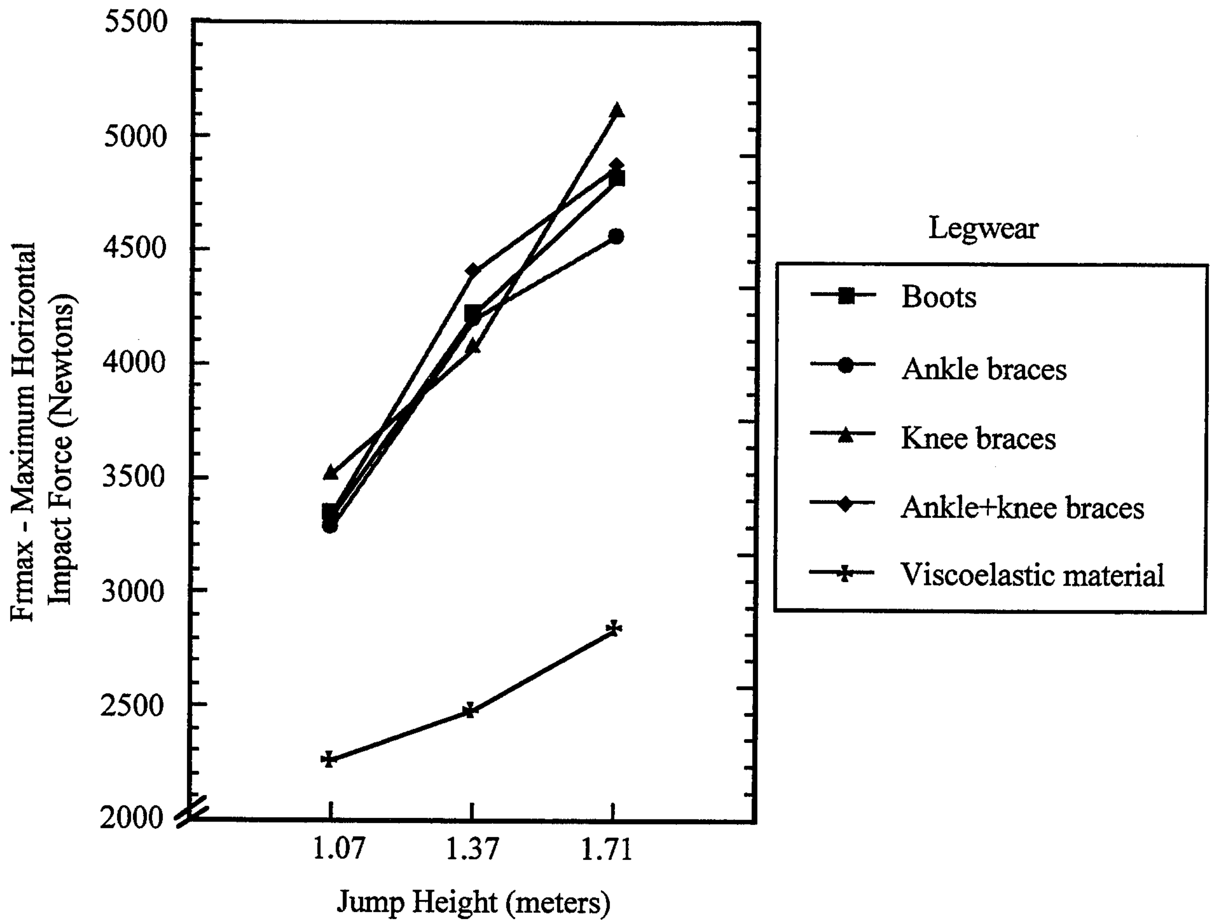

Figure 14. Experiment I: Maximum horizontal impact force versus jump height by legwear.

Vertical Force During Maximum Horizontal Impact (Fzmxr)

During the maximum horizontal impact event, soldiers' landings produced vertical impact forces (Fzmxr), averaging 3605 N to 5215 N. Impact absorbance for Fzmxr differed significantly between 1.07-m jumps and those from 1.37 m or 1.71 m. ANOVA results in Table 7 also indicate that Fzmxr results differed across legwear conditions. Wearing only boots, knee braces, or the combination of ankle and knee braces greatly increased Fzmxr values at maximum horizontal impact, while the viscoelastic material reduced Fzmxr by 1500 N. Table 8 summarizes the legwear averages for Fzmxr.

Table 8

Experiment I: Vertical Impact Forces

Legwear	Vertical impact Fzmxr	Forces (N) Fzend
Boots	4120.51	1092.91
Boots + ankle braces	4010.21	1048.14
Boots + knee braces	4232.67	1199.63
Boots + ankle and knee braces	4200.71	1130.45
Viscoelastic material	2522.44	1104.00

Vertical Force at Toe Touchdown (Fzfl)

At toe touchdown, soldiers' PLFs had greater vertical impact forces when jump height increased: 4430 N (5.6 times body weight) for 1.07 m jumps, 5700 N (6.6 times body weight) at 1.37 m, and 6930 N (8.5 times body weight) at 1.71 m. Table 7 summarizes the statistical results for Fzfl. Surprisingly, the ankle braces allowed the lowest Fzfl measures. As seen in Figure 15, the ankle braces' performance was significantly better than that for landings in boots only or the combination of ankle and knee braces.

Horizontal Force During Toe Touchdown (Frfl)

ANOVAs revealed that jump height and legwear conditions produced highly significant differences between the horizontal force measurements at toe touchdown (see Table 7). These force measurements, Frfl, averaged 2350 N, 2760 N, and 3140 N for the three jump heights (1.07 m, 1.37 m, and 1.71 m). Figure 16 indicates the viscoelastic landing surface afforded significantly lower Frfl impact forces than did the other legwear conditions. Landings on this viscoelastic material averaged horizontal toe touchdown forces of 1550 N which were 50% less than the other force measurements. Surprisingly, the viscoelastic material seemed to dampen the soldier's horizontal impact forces to this 1500-N level over the three jump heights.

The interaction of jump height and legwear conditions also significantly affected soldiers' Frf1 results. Evidence of this interaction is given in Figure 16 since ankle braces and the combination ankle-knee braces conditions cause similar Frf1 levels. Also, when jump height increased, the force-attenuating performance of the boots only and knee braces approaches reversed, with the knee braces having the largest horizontal forces at toe touchdown when impact velocity increased.

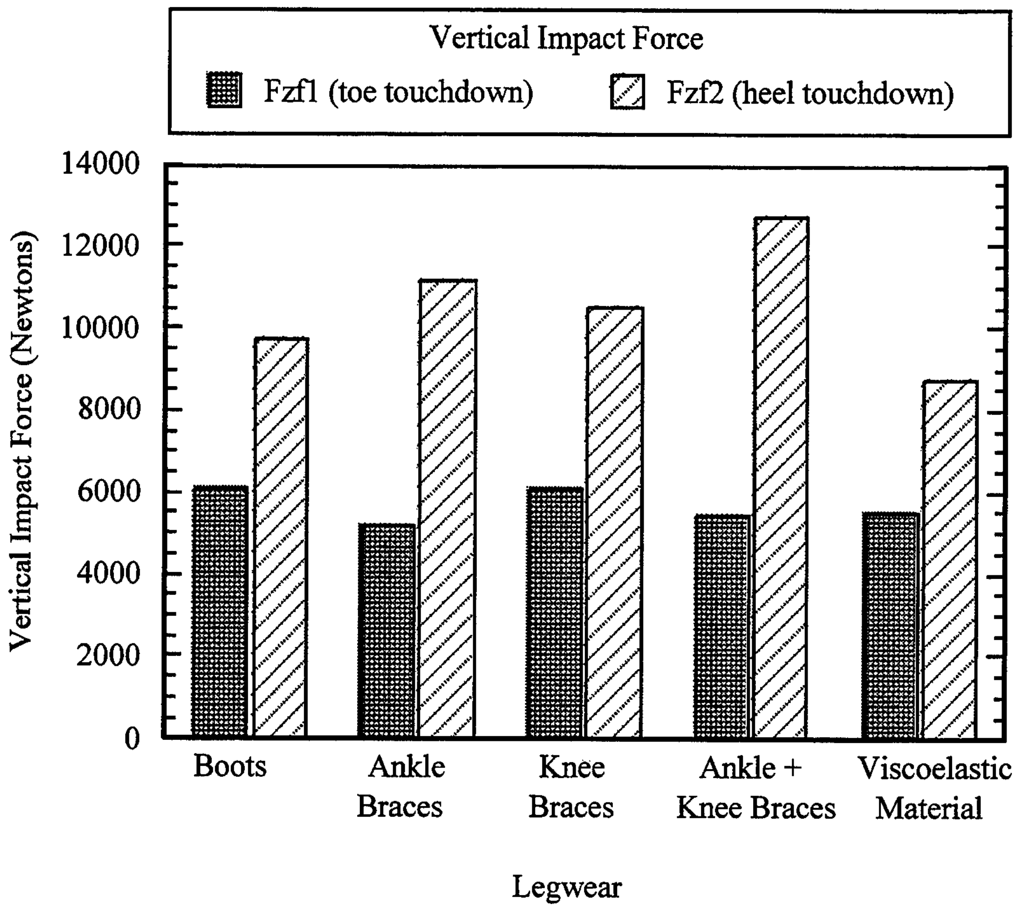

Figure 15. Experiment I: Vertical ground reaction forces at the first two impact events by legwear.

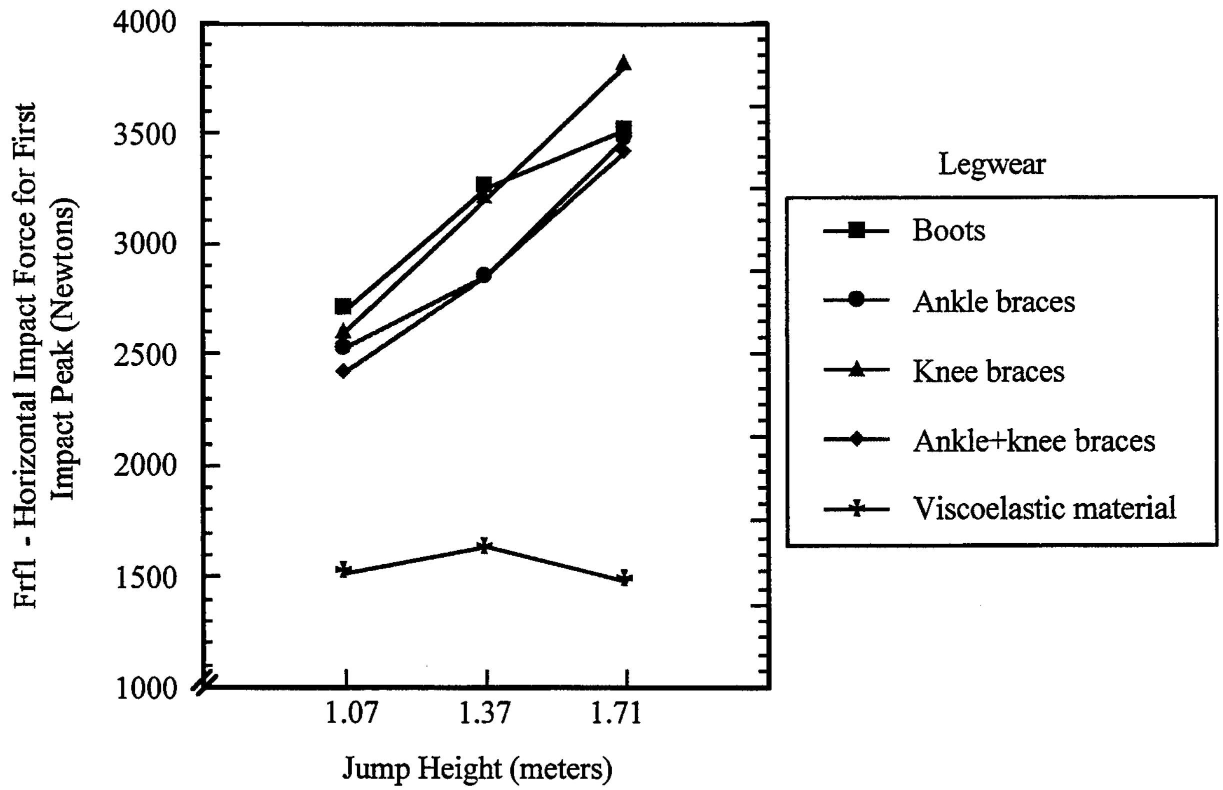

Figure 16. Experiment I: Horizontal impact force during the first impact peak versus jump height by legwear.

Vertical Force at Heel Touchdown (Fzf2)

Statistical results for heel touchdown, F2 impact, paralleled toe touchdown since both jump height and legwear conditions caused significant differences in vertical force results (see Table 7). As jump height elevated, the Fzf2 measures averaged 7170 N to 14150 N or 10 to 20 times soldiers' body weights. Figure 15 reveals that the viscoelastic landing surface had the lowest Fzf2 average. Scheffé testing indicated that its impact absorption performance was superior to the three braces' approaches.

Horizontal Force at Heel Touchdown (Frf2)

Both jump height and legwear conditions produced significantly different horizontal impact forces during the PLF heel touchdown event. As indicated in Table 7, Frf2 statistical results are similar to those for Frf1. Increasing jump height again produced larger Frf2 impacts; however, only the difference between the 1.07-m and 1.71-m force averages was significant. At heel touchdown, the force-attenuation superiority of the viscoelastic material was again evident. Landings on the viscoelastic material produced a significantly lower Frf2 average of 722 N, while the boots, ankle braces, knee braces, and combination ankle-knee braces conditions averaged 1600 N, 1541 N, 1670 N, and 1630 N, respectively. Examination of Figure 17 indicates there is also an interaction effect between jump height and legwear on Frf2 measures. Wearing ankle braces alone or in combination with knee braces resulted in a leveling of Frf2 forces during 1.37-m and 1.71-m jumps, while landing with the boots only or knee braces increased Frf2 forces. This divergence of force-attenuation performance drove the statistical interaction results.

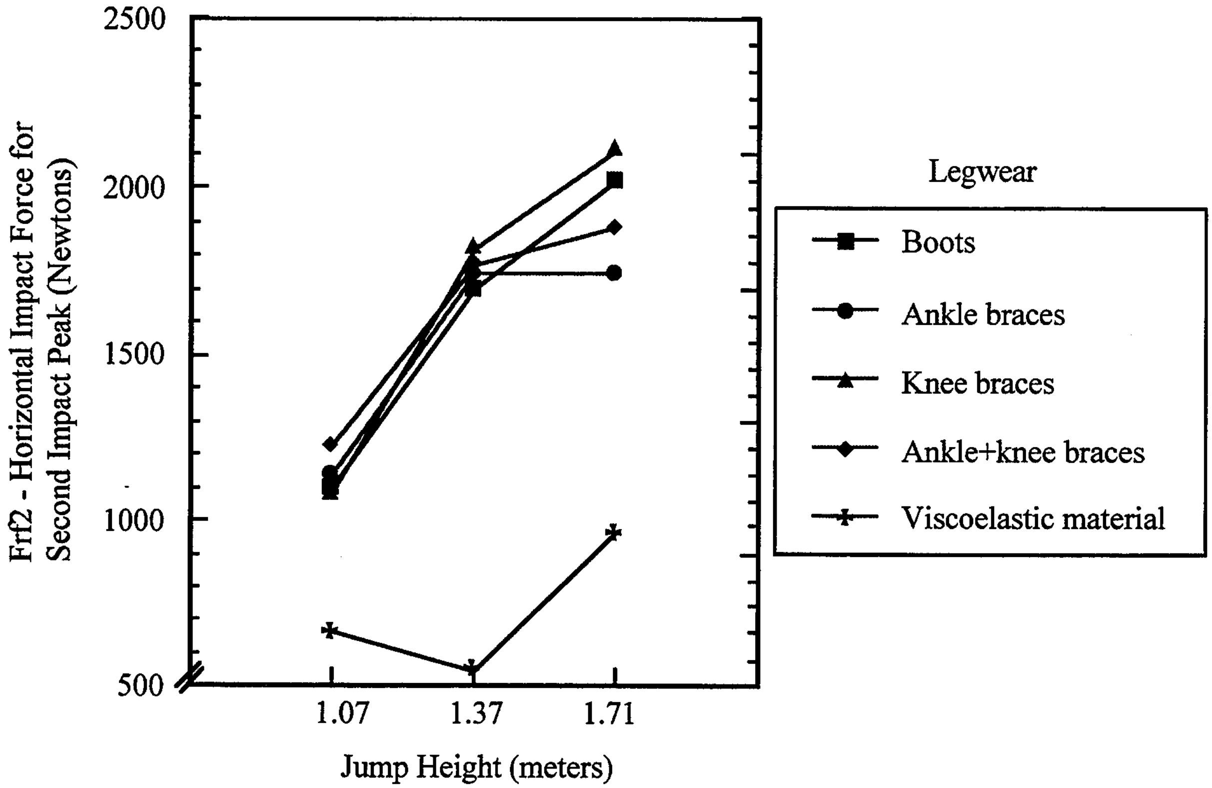

Figure 17. Experiment I: Horizontal impact force during the second impact peak versus jump height by legwear.

Impact at the End of Reactive Absorption (Fzend, Frend)

At the end of reactive absorption, we believe a soldier's PLF performance becomes more active or directed in movement and control. During this event, soldiers have typically completed initial impact absorption at the feet and will begin rolling up on their toes to start the impact of the lower extremities and completion of the PLF. The vertical and horizontal forces accompanying the end of reaction absorption, Fzend and Frend, did not vary much in magnitude. As shown in Table 7, only legwear conditions significantly affected Fzend measures. Soldiers' landings with the knee braces had the largest Fzend average, 1200 N, which was significantly larger than the Fzend forces recorded for landings with boots only, the ankle-knee braces' combination, or on the viscoelastic material (see Table 8). Generally, the Fzend forces ranged from 1.2 to 1.5 times a soldier's body weight. Table 7 indicates that variation in jump height only produced statistically significant differences in Frend. These horizontal forces averaged 597 N to 798 N, 0.7 to 1.0 times a soldier's body weight.

Percent Force Change Between Legwear Approaches and Boots

To better examine the attenuation effects of the bracing and viscoelastic material approaches, we calculated the percent change of their accompanying impact forces with respect to the baseline, boots only impact forces. Twelve values of percent change, four legwear comparisons at the three jump heights, were computed for the maximum vertical impact forces and maximum horizontal resultant forces. As shown in Table 9, only the legwear conditions produced significant differences in these percent change values, Pdfzmax and Pdfrmax. For both percent change calculations, Table 10 indicates that only the viscoelastic material approach afforded a force reduction, 7.2% for Pdfzmax and 36.8% for Pdfrmax. Post hoc testing revealed that the viscoelastic material's performance was significantly better than the other bracing approaches. The Pdfzmax calculation for maximum vertical impact indicated a large force increase for the ankle-knee brace combination landings that was significantly worse when compared to the other legwear conditions.

Table 9

Experiment I: ANOVA Results for Percent Changes of Maximum Vertical and Horizontal Resultant Forces

Variable	Effect	F-ratio	*p*-value
Pdfzmax	Jump height	F(2,22)= 1.42	ns
	Legwear	F(3,21)= 28.12	*p*<.001
	Jump height x legwear	F(6,18)= 0.73	ns
Pdfrmax	Jump height	F(2,20)= 0.31	ns
	Legwear	F(3,19)= 36.68	*p*<.001
	Jump height x legwear	F(6,16)= 1.55	ns

Table 10

Experiment I: Percent Change in Impact Forces by Bracing and Force-Attenuating Legwear

Legwear	Percent change in maximum vertical impact force	Percent change in maximum horizontal impact force
Ankle braces	16.4	1.7
Knee braces	11.0	9.6
Ankle and knee braces	31.7	8.3
Viscoelastic material	-7.2	-36.8

Note. Percent changes were calculated with respect to combat boot landing impact forces and averaged for descent velocities 4.57, 5.18, and 5.79 m/s. Negative values indicate force reductions, and positive values denote force increases.

Moments

We measured the vertical moments accompanying the impact events of the PLF. These performance variables allowed us to examine the torsional effects of the PLF, a leading injury mechanism. The vertical moments were defined as the torques about the vertical axis passing through the center of pressure (a point on the force plate within the landing contact area defined by the soldier's feet). The moment performance variables discussed here are ground reaction moments that occurred at the paratrooper's feet. To facilitate statistical analysis, we used the absolute values of the moment measurements. Table 11 lists ANOVA results for moment measurements.

Table 11

Experiment I: ANOVA Results for Moments About the Vertical Axis

Variable	Effect	F-ratio	*p*-value
Mzmax	Jump height	F(2,19)= 20.15	$p<.001$
	Legwear	F(4,17)= 5.39	$p<.01$
	Jump height x legwear	F(8,13)= 1.38	ns
Mzfzmx	Jump height	F(2,22)= 8.40	$p<.01$
	Legwear	F(4,20)= 12.46	$p<.001$
	Jump height x legwear	F(8,16)= 1.36	ns
Mzfrmx	Jump height	F(2,18)= 7.53	$p<.01$
	Legwear	F(4,16)= 4.57	$p<.05$
	Jump height x legwear	F(8,12)= 0.61	ns
Mzf1	Jump height	F(2,20)= 0.40	ns
	Legwear	F(4,18)= 1.98	ns
	Jump height x legwear	F(8,14)= 1.59	ns
Mzf2	Jump height	F(2,20)= 10.67	$p<.01$
	Legwear	F(4,18)= 4.76	$p<.01$
	Jump height x legwear	F(8,14)= 1.31	ns
Mzend	Jump height	F(2,20)= 3.79	$p<.05$
	Legwear	F(4,18)= 3.00	$p<.05$
	Jump height x legwear	F(8,14)= 0.54	ns

Maximum Vertical Moment (Mzmax)

Generally, the maximum vertical moment occurred between the second impact peak and the end of reactive absorption. As indicated in Table 11, both jump height and legwear conditions significantly affected this measurement, Mzmax. When jump heights were increased, the soldiers experienced larger torsional forces about their feet: 5292 Nm, 9078 Nm, and 12000 Nm for the heights 1.07 m, 1.37 m, and 1.71 m, respectively. When compared to the boots-only landings, all the attenuation legwear conditions did reduce the maximum vertical moment. However, only the viscoelastic material approach allowed a significant reduction of 6200 Nm (see Figure 18). Thus, the viscoelastic material appears to attenuate both impact and torsional effects of the PLF.

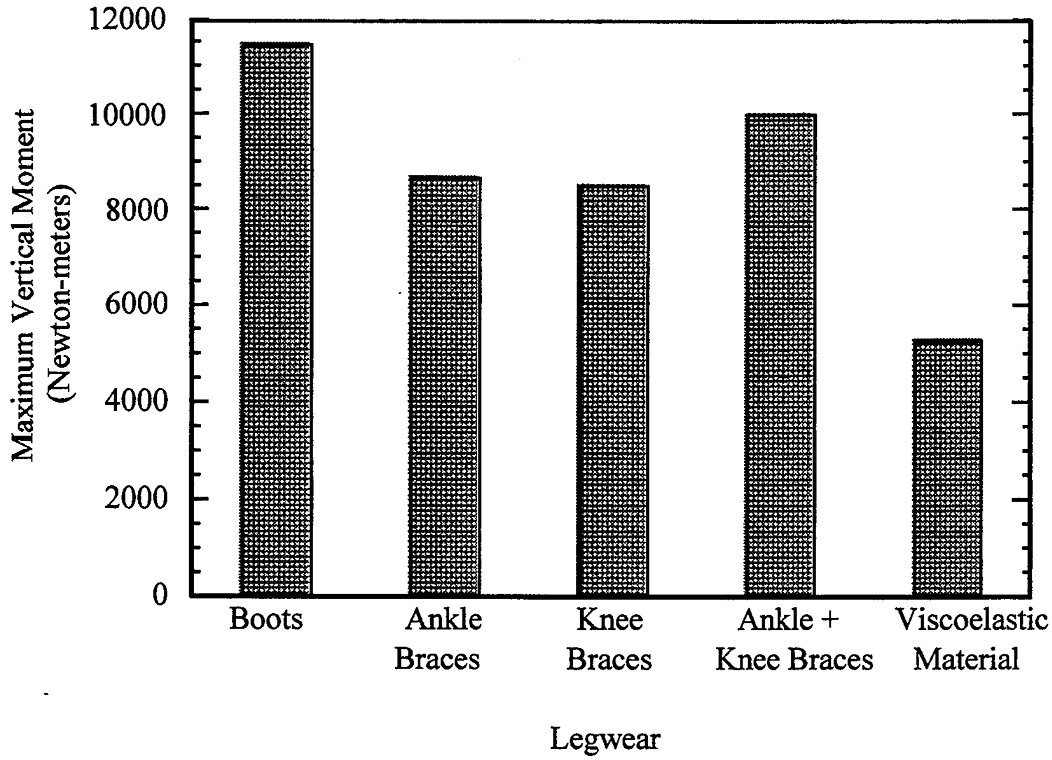

Figure 18. Experiment I: Maximum moment about the vertical axis by legwear.

Vertical Moments at Maximum Vertical and Horizontal Impact (Mzfzmax and Mzfrmax)

Vertical moments were also measured during the maximum vertical and horizontal impact events, Mzfzmax and Mzfrmax. We wanted to examine if significant torsional effects accompanied these large forces. As listed in Table 11, statistical analyses revealed that both jump height and legwear conditions produced significant differences in Mzfzmax and Mzfrmax measures. At maximum vertical impact, jumps from 1.37 m produced ground reaction moments averaging 2142 Nm, while 1.71 m landings averaged 3168 Nm. Paralleling vertical force results, soldiers' landings with the ankle-knee braces combination had the highest Mzfzmax results, 3783 Nm. Apparently, this brace combination caused more torsion during heel touchdown. As shown in Table 12, this performance effect was significantly worse than the moments produced by the viscoelastic material and boots-only conditions.

Similar to the results for Mzfzmax, the vertical moment at maximum horizontal impact increased with jump height elevation. Mzfrmax measurements were significantly greater when landing from 1.71 m, 5551 Nm, as opposed to the moments of 2717 Nm and 3553 Nm for the 1.07-m and 1.37-m jump heights. Tukey's HSD Test revealed that the viscoelastic material reduced torsion about the feet during maximum horizontal impact. The moment averages listed in Table 12 indicate that this approach was significantly better than the boots, ankle braces, or ankle-knee braces combination approaches.

Table 12

Experiment I: Moments About the Vertical Axis

Legwear	Vertical moments (Nm) Mzfzmax	Mzfrmax	Mzf2
Boots	2094.57	4789.71	2340.43
Boots + ankle braces	2474.38	4361.83	2527.83
Boots + knee braces	2462.21	4002.28	2274.06
Boots + ankle and knee braces	3782.56	4305.95	3893.77
Viscoelastic material	1559.97	2241.08	1671.57

Vertical Moment at Toe Touchdown (Mzf1)

Statistical analyses determined that jump height and legwear conditions produced no significant differences in the vertical moments measured at toe touchdown. See Table 11 for a summary of these Mzf1 results.

Vertical Moment at Heel Touchdown (Mzf2)

During heel impact, soldiers' PLFs produced significantly greater vertical moments as jump height increased. These moments averaged 2038 Nm, 2268 Nm, and 3319 Nm for the three jump heights. Besides jump height influences, Table 11 reveals that the different legwear conditions significantly affected Mzf2 measurements. As expected, these moment measurements were the lowest on the viscoelastic landing surface and the highest when the ankle-knee braces' combination was worn (see Table 12). Scheffé testing indicated landing with the ankle-knee braces combination produced significantly greater vertical moments than landings in the boots only, knee braces, and viscoelastic material conditions.

Vertical Moment at the End of Reactive Absorption (Mzend)

The vertical moments accompanying the end of reactive absorption were generally smaller than those recorded for the other impact events. These moment measurements ranged between 1135 Nm and 1623 Nm. The ANOVA results listed in Table 11 indicate that the different jump height and legwear conditions significantly affected Mzend values. Elevating jump height did increase Mzend. When soldiers wore the combination of ankle and knee braces, they experienced vertical moments about the feet nearly 500 Nm greater than the moments recorded for the viscoelastic padded landings. Moment averages for the other three legwear approaches were similar.

Impulses

Since vertical impact forces are a major mechanism for PLF injuries, we decided to measure absorption of these forces during the periods of the reactive landing phase. We calculated the vertical impulses by integrating the absorption of vertical force over time. Because both interval length and force amplitude determine these impulse measurements, evaluation of the attenuation legwear performance should look for larger absorption intervals and lower force amplitudes. See Table 13 for a summary of the statistical analysis results for the impulse measurements.

Vertical Impulse to Toe Touchdown (Impf1)

Paratroopers' vertical force absorption between initial contact and the first impact peak, Impf1, was significantly affected by the jump height and legwear worn (see Table 13). Impulse calculations indicated that increasing jump height required greater force absorption by the paratroopers: 26.06 Ns, 29.67 Ns, and 31.25 Ns for the three heights, lowest to highest, respectively. As seen with the previous force and moment performance measures, the viscoelastic material allowed the greatest force absorption, 32.24 Ns, until the F1 impact event. Landings on the viscoelastic material afforded paratroopers a longer absorption time during impact. As shown in Table 14, PLFs performed in knee braces and the boots-only conditions resulted in lower impulse averages. However, the accompanying impact forces remained higher than those measured for landings on the viscoelastic material. When soldiers wore ankle braces either alone or with knee braces, the impulses decreased because of lower impact forces and absorption times experienced over the F1 interval. Post hoc testing revealed that these impulse reductions were significant when compared to the other legwear.

Table 13

Experiment I: ANOVA Results for Vertical Force Impulses

Variable	Effect	F-ratio	*p*-value
Impf1	Jump height	F(2,20)= 24.27	$p<.001$
	Legwear	F(4,18)= 16.32	$p<.001$
	Jump height x legwear	F(8,14)= 0.53	ns
Impf2	Jump height	F(2,20)= 42.25	$p<.001$
	Legwear	F(4,18)= 3.54	$p<.05$
	Jump height x legwear	F(8,14)= 1.90	ns
Impf12	Jump height	F(2,20)= 35.21	$p<.001$
	Legwear	F(4,18)= 1.44	ns
	Jump height x legwear	F(8,14)= 1.96	ns
Impf2end	Jump height	F(2,20)= 0.56	ns
	Legwear	F(4,18)= 4.50	$p<.05$
	Jump height x legwear	F(8,14)= 1.70	ns

Table 14

Experiment I: Vertical Force Impulses During Impact Events

	Vertical force impulses (Ns)		
Legwear	Impf1	Impf2	Impf2end
Boots	30.38	119.49	210.49
Boots + ankle braces	26.19	117.88	204.33
Boots + knee braces	30.60	125.19	216.65
Boots + ankle and knee braces	25.56	120.16	216.27
Viscoelastic material	32.24	121.84	217.66

Vertical Impulse to Heel Touchdown (Impf2)

The vertical impulses were considerably larger for the period between contact and the F2 impact peak, Impf2. As indicated in Table 13, jump height greatly affected this impulse measurement. Again, with increases in jump height, soldiers experienced greater impulses driven by larger impact forces and shorter absorption times. The impulses averaged 109.47 Ns, 122.80 Ns, and 130.46 Ns for the three jump heights. ANOVAs and Tukey's HSD Test revealed significant impulse differences for knee brace landings versus the boots-only, ankle braces, or combination ankle-knee braces' conditions (see Table 14). Larger impulses were recorded for landings in the knee braces' condition because of a large F1 impact force and a longer time interval for the F2 period. When soldiers performed PLFs wearing the ankle braces or the ankle-knee braces' combination, the opposite conditions occurred to produce lower impulse results. The ankle brace impulse results were not optimal since absorption time was too short to dissipate the high impact forces. Table 14 summarizes the vertical impulse averages by legwear conditions.

Vertical Impulse Between Toe and Heel Touchdown (Impf12)

Examination of the force absorption between the two impact peaks, Impf12, revealed significant differences only for jump height variation (see Table 13). During this period, soldiers' PLFs produced vertical impacts that ranged from 87.85 Ns to 106.14 Ns. Again, increasing jump height caused greater vertical impact and drove Impf12 impulse results.

Vertical Impulse Between Heel Touchdown and the End of Reactive Absorption (Impf2end)

During the last period of the reactive landing phase, jump height conditions did not significantly determine soldiers' vertical force absorption (Impf2end). However, the vertical impulse measurements did vary for the five legwear approaches (see Table 13). Between the second impact peak and the end of reactive absorption, soldiers' PLFs progressed from heel contact through knee bending to a minimum knee angle. Table 14 indicates that the soldiers' PLFs in the ankle brace condition produced the lowest Impf2end value as compared to the other legwear. The impulse result was attributable to the small vertical force recorded at the end of the reactive absorption. Because of large impact forces at the end of the reactive landing period, the knee brace had one of the largest impulse results for Impf2end. This impulse performance during the knee brace condition paralleled the Impf2 results. The viscoelastic material produced the largest impulse measurement since it afforded a large absorption time and lower vertical forces. (See Table 14 for a listing of the Impf2end averages.)

Absorption Times

PLF time intervals were defined by the impact events during the reactive landing period. These absorption times are important to delineate between the effects of the impact attenuation approaches and examine how jump height affects performance. To lessen the torsional and vertical force effects experienced during the PLF, it is imperative that absorption times are increased. Table 15 summarizes the ANOVA results for time measurements.

Table 15

Experiment I: ANOVA Results for Impact Times

Variable	Effect	F-ratio	*p*-value
Frmaxtime	Jump height	F(2,18)= 0.38	ns
	Legwear	F(4,16)= 4.09	*p*<.05
	Jump height x legwear	F(8,12)= 0.58	ns
F1time	Jump height	F(2,20)= 30.48	*p*<.001
	Legwear	F(4,18)= 16.39	*p*<.001
	Jump height x legwear	F(8,14)= 1.03	ns
F2time	Jump height	F(2,20)=104.12	*p*<.001
	Legwear	F(4,18)= 48.09	*p*<.001
	Jump height x legwear	F(8,14)= 0.99	ns
F12time	Jump height	F(2,20)= 74.78	*p*<.001
	Legwear	F(4,18)= 34.00	*p*<.001
	Jump height x legwear	F(8,14)= 0.79	ns
F2endtime	Jump height	F(2,20)= 18.61	*p*<.001
	Legwear	F(4,18)= 12.04	*p*<.001
	Jump height x legwear	F(8,14)= 0.25	ns
Total time	Jump height	F(2,20)= 32.80	*p*<.001
	Legwear	F(4,18)= 19.28	*p*<.001
	Jump height x legwear	F(8,14)= 0.22	ns

Time to Toe Touchdown (F1time)

F1time measurements, the interval between initial contact and the first impact peak, differed significantly during the jump height and legwear conditions. For the three jump heights, soldiers' PLFs produced F1times of 14.8 msec, 13.6 msec, and 12.6 msec for the lowest to highest heights, respectively. The increased descent velocities caused these reduced impact times. As shown in Table 16, the legwear conditions produced important differences in F1 impact times. Only the viscoelastic material condition increased the absorption time to the F1 impact peak. Scheffé tests indicated it was statistically superior to all the other legwear. In contrast, while wearing the ankle and knee braces together, soldiers experienced the first impact peak much quicker, 12.5 msec after initial contact.

Table 16

Experiment I: Time Intervals During the Reactive Landing Phase

Legwear	Time intervals (msec) F1time	F2time	F12time	F2endtime	Totaltime
Boots	14.0	36.0	22.0	83.0	119.0
Boots + ankle braces	13.0	31.7	18.8	78.1	109.8
Boots + knee braces	13.9	35.0	21.1	76.6	111.6
Boots +ankle and knee braces	12.5	29.9	17.4	71.0	100.9
Viscoelastic material	14.8	35.7	20.9	87.0	122.7

Time to Maximum Horizontal Impact (Frmaxtime)

Generally, the maximum horizontal impact event followed the first impact peak. Only the legwear conditions produced significant differences in Frmaxtime, the time between initial contact and the peak horizontal resultant impact force (see Table 15). When soldiers made jumps wearing combat boots, their resulting Frmaxtime was the shortest as compared to the other legwear conditions, 22.5 msec. Oppositely, the paratroopers' landings on the viscoelastic material produced Frmaxtimes averaging 27.4 msec, which post hoc testing revealed as statistically greater than the impact time for boots only landings. The ability of the viscoelastic material to increase absorption time parallels its force attenuation results for Frmax.

Time to Heel Touchdown (F2time)

The ANOVA results in Table 15 indicate that both jump height and legwear conditions produced highly significant differences in F2time, the time between initial impact and the second impact peak (heel touchdown). Similar to F1time results, soldiers experienced the second vertical impact much faster when they landed from greater jump heights: F2times averaged 38.3 msec, 33.3 msec, and 29.4 msec for the 1.07-m, 1.37-m, and 1.71-m heights, respectively. The various legwear conditions also caused statistically important differences in the F2times. When compared to the boots-only condition, none of the attenuating legwear approaches increased the force absorption time to the F2 peak. Post hoc comparisons indicated that wearing ankle braces alone or in combination with the knee braces resulted in PLF performances with much lower absorption time than the other legwear conditions. (See Table 16 for a listing of these F2time averages.)

Time Between Toe and Heel Touchdown (F12time)

The ANOVA results for F12time, the interval between initial impact peaks, are similar to those for F2time (see Table 15). F12times averaged 16.8 msec to 23.5 msec. Scheffé results for the jump height and legwear paired comparisons also paralleled those of F2time. F12time averages for the experiment's legwear conditions are shown in Table 16.

Time Between Heel Touchdown and End of Reactive Absorption (F2endtime)

The last time interval of the reactive landing phase is F2endtime. This period follows the F2 impact until the end of reactive absorption. As shown in Table 15, jump height and legwear conditions greatly affected F2endtime results. Similar to other time interval measurements, F2endtime also decreases with increasing jump height: 88.5 milliseconds, 80.5 msec, and 68.4 msec for 1.07 m, 1.37 m, and 1.71 m, respectively. When soldiers wore the ankle and knee braces together, the last interval of the reactive absorption period was much shorter than the times measured for landings in boots only or on the viscoelastic padding. In addition, Scheffé tests revealed that the viscoelastic landing surface allowed the soldiers to experience greater F2endtime absorption than wearing ankle braces or knee braces (see Table 16).

Total Reactive Absorption Time (totaltime)

Totaltime, the absorption interval from initial contact to the end of reactive absorption, was also measured. Since the reactive landing phase encompasses the period of greatest impact effects, this time period became an important performance parameter to evaluate impact attenuation equipment. Again, jump height and legwear produced highly significant differences in totaltime (see Table 15). Scheffé testing revealed large differences among the time averages for the three jump heights: 126.8 msec, 113.8 msec, and 97.8 msec. Surprisingly, no attenuating or bracing legwear approach provided a statistically significant improvement over the boots only condition. According to Table 16, landings made in the ankle and knee brace combination had greatly reduced absorption times when compared to all the other legwear conditions. Oppositely, the viscoelastic material offered increased absorption time opportunity with respect to the other bracing legwear approaches.

Joint Angles

We also examined soldiers' ankle and knee angles during the PLF events of reactive absorption. Because of differences in soldiers' PLF techniques, we did not use the absolute angles measured during impact events. Instead, we calculated the change in angle that we termed as "bend" between the various impact events: contact, the F1 impact peak, the F2 impact peak, and the end of the reactive landing phase. For these impact events, we measured the ankle angle as the angle between the anterior side of the lower leg (calf) and the superior surface of the foot. The knee angle was determined as the angle between the posterior sides of the upper leg (thigh) and lower leg (calf). Because of the complexity in filming the paratroopers' PLFs, we were only able to capture ankle and knee angles at the contact, F1 and F2 impact events.

As soldiers bend their knees and ankles during the PLF technique, this motion of the leg segments about the joints facilitates impact absorption. This facilitation occurs through the lengthening of soldier's tensed muscles to dissipate impact and increase absorption time. Therefore, increased joint bending is important to mitigate the impact effects. ANOVA results for these angle variables are given in Table 17.

Ankle Bend

Ankle bend was measured for three intervals of reactive absorption: the change in angle between initial contact and the first impact peak (Caaf1); ankle bend between the two impact peaks (Caaf12); and the total angle change between initial contact and the second impact peak (Caaf2). We wanted to examine if the changes in ankle angle during these intervals were affected by jump height or legwear.

Table 17

Experiment I: ANOVA Results for Changes in Ankle and Knee Angles

Variable	Effect	F-ratio	*p*-value
Caafl	Jump height	F(2,13)= 35.11	*p*<.001
	Legwear	F(4,11)= 11.88	*p*<.01
	Jump height x legwear	F(8, 7)= 1.34	ns
Caaf2	Jump height	F(2,13)= 57.08	*p*<.001
	Legwear	F(4,11)= 18.01	*p*<.001
	Jump height x legwear	F(8, 7)= 3.22	ns
Caaf12	Jump height	F(2,13)= 35.84	*p*<.001
	Legwear	F(4,11)= 21.85	*p*<.001
	Jump height x legwear	F(8, 7)= 3.60	ns
Ckafl	Jump height	F(2,13)= 9.24	*p*<.01
	Legwear	F(4,11)= 2.35	ns
	Jump height x legwear	F(8, 7)= 0.45	ns
Ckaf2	Jump height	F(2,13)= 5.22	*p*<.05
	Legwear	F(4,11)= 4.18	*p*<.05
	Jump height x legwear	F(8, 7)= 1.65	ns
Ckaf12	Jump height	F(2,13)= 7.79	*p*<.01
	Legwear	F(4,11)= 7.31	*p*<.01
	Jump height x legwear	F(8, 7)= 0.50	ns

Paratroopers' ankle angles for initial contact ranged between 83° to 90°, while at the first impact peak, the ankle angles averaged 72° to 75°. The ankle bend results for Caafl revealed highly significant differences for jump height and legwear conditions (see Table 17). Similar to the results for absorption times during the F1 interval, increased jump heights produced significantly smaller changes in the ankle angle. Whenever soldiers wore the ankle brace, either alone or with the knee brace, they did not bend their ankles as much as when landing during the other legwear conditions. For Caafl, the ankle bend averaged 11.3° on ankle brace landings and 10.5° with the ankle and knee brace combination. Landings with boots, knee braces, and the viscoelastic landing surface allowed ankle bend of 14°, 15.1°, and 14.7°, respectively. Figure 19 shows the ankle angles present at contact and the F1 impact peak.

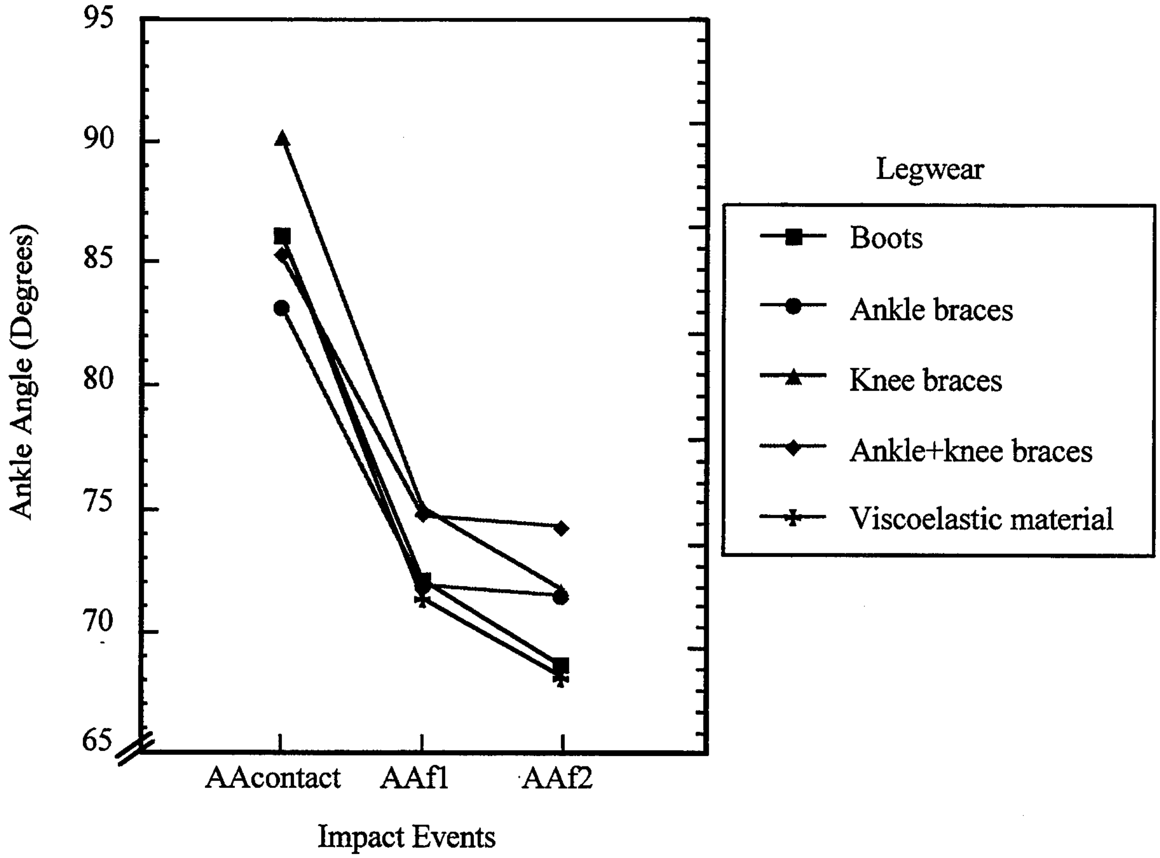

Figure 19. Experiment I: Ankle angles versus impact events by legwear.

According to Table 17, jump height and legwear significantly affected paratrooper ankle bend between toe and heel contact, Caafl2. Because of the short time between impacts F1 and F2, the change in paratroopers' ankle angles was small, ranging from 0.2° to 4.4°. As expected, soldiers' PLFs produced smaller ankle bends when jump heights increased. At the 1.71-m jump height, this change was barely perceptible. Post hoc comparisons again revealed that wearing ankle braces was restrictive to ankle bend. This is evident in Figure 19.

As seen in Figure 19, the ankle bend averaged 11° to 20° during the interval between initial contact and the second impact. The results in Table 17 indicate that jump height played a significant role during the initial landing phase of the PLF. Parallel to time and force results, higher heights do not allow the PLF motions of bending and twisting to produce as much impact reduction. Therefore, improved paratrooper legwear is imperative. Similar to the previous ankle bend findings, the ankle braces are restrictive during the contact-F2 interval. Surprisingly, the knee braces allowed the soldiers the greatest ankle bend (see Figure 19).

Knee Bend

We also calculated the knee bend during various impact events and evaluated the importance of jump height and legwear on the results (see Table 17). Paratroopers' knee bend measurements between initial contact and the first impact peak, Ckaf1, were only affected by jump height. Opposite to the results for the ankle bend, increases in jump heights produced greater knee bend: 14.6° for 1.07 m, 16.5° for 1.37 m, and 17.2° for 1.71 m. During the interval between initial contact and F1 impact, there appears to be a trade-off: for lower jump heights or impact velocities, the ankle bend is used more for impact absorption, while the knee bend becomes important for higher heights. Figure 20 presents the knee angle averages for contact and F1 impact.

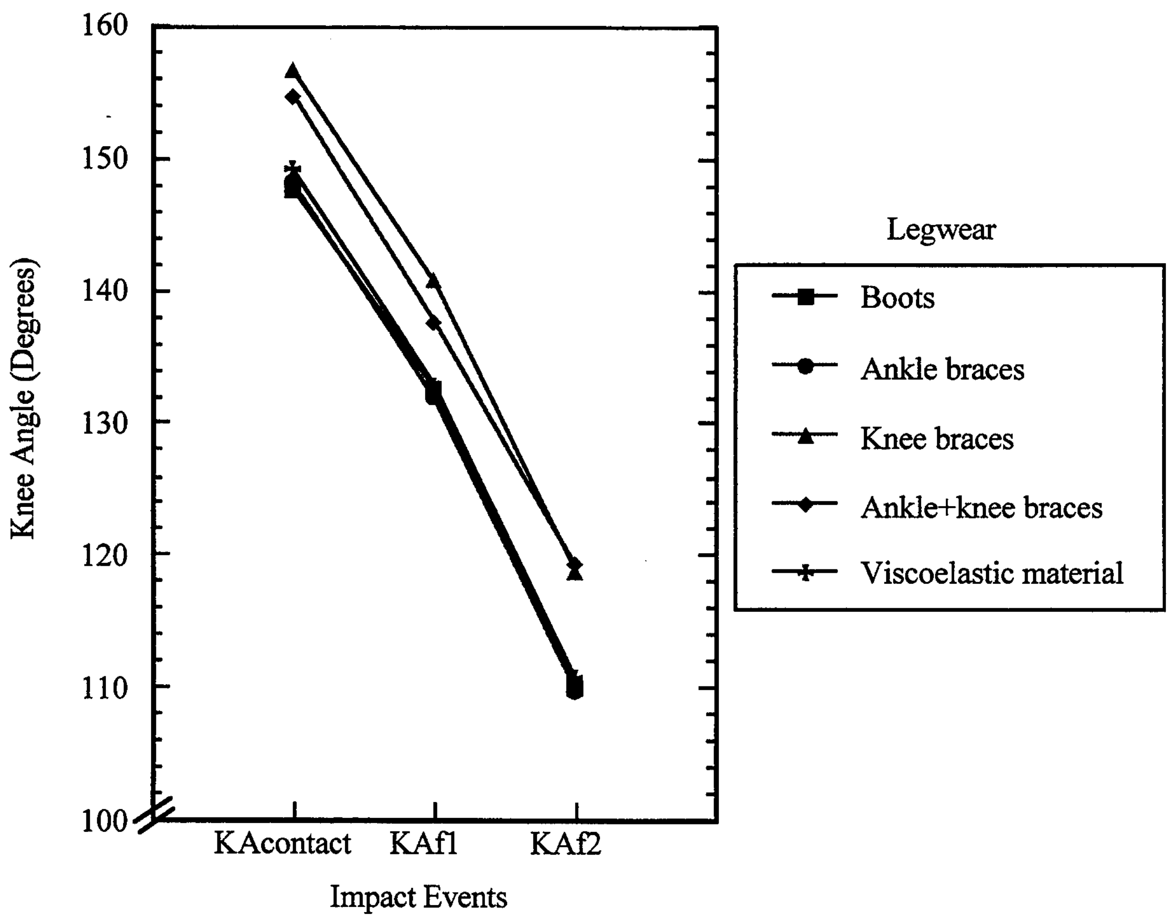

Figure 20. Experiment I: Knee angles versus impact events by legwear.

Between the F1 and F2 impact peaks, paratroopers increased their knee bend (decreased knee angle) between 18.4° and 22.2°. Since the knee bend was greater for this interval than the contact-F1 interval, the ANOVA results were very similar for the knee bend calculations, Ckafl2 and Ckaf2 (changes in knee angle during the F1-F2 interval and the contact-F2 interval). Table 17 indicates that variations in jump height and legwear significantly contributed to the differences among Ckafl2 and Ckaf2 measurements. Post hoc comparisons revealed that soldiers' knee bends were greatest at the intermediate jump height (1.37 m): 22.2° and 38.7° for Ckafl2 and Ckaf2. In addition, when soldiers wore ankle and knee braces together, this legwear approach significantly restricted knee bend (see Figure 20). We propose that this restriction is responsible for the large F2 impact forces that occurred for this legwear condition.

Subjective Measures

Post-jump and post-study surveys were used to provide subjective feedback about the effects of jump height and legwear conditions on PLF performance. With the post-jump survey, we were able to quickly capture the soldier's impressions about his PLF performance during the 15 landings. Soldiers' ratings of overall landing performance, mobility, initial landing contact, and rolling capability were made with respect to previous PLF experiences. Most of the soldiers participating in this study had performed at least 20 PLFs since airborne training.

Hierarchical loglinear testing was used on the soldiers' landing ratings: overall landing opinion (Rlandopn); walking and pre-jump posture mobility (Mobopn); initial landing contact opinion (Ilandopn); and rolling and twisting feasibility opinion (Rollopn). This nonparametric type of regression analysis determined whether jump height or legwear conditions affected soldiers' perceptions about their landings. Because the viscoelastic material was not incorporated into the soldiers' legwear, they did not provide mobility nor rolling opinions for landings on the viscoelastic material.

The soldiers' ratings were tabulated into cells according to opinion, jump height, and legwear categories. Results indicated that all cells did not have responses. Therefore, a Δ of 1.0 was added to each cell frequency before hierarchical loglinear analysis was performed. In addition, the rating options for Rlandopn were compressed into three levels "softer," "average," and "harder." The three rating levels for the Mobopn, Ilandopn, and Rollopn variables included "easier," "more difficult," and "no different than usual."

Hierarchical loglinear analysis of the four opinions revealed no three-way interactions among opinion, jump height, and legwear. Thus, a simpler model involving main effects of opinion, jump height, and legwear, along with their respective two-way interactions sufficed to explain PLF ratings. Through the SPSS program, partial association tests revealed the significant effects for four opinion variables. These effects are summarized in Table 18.

Table 18

Experiment I: Significant Hierarchical Loglinear Results for Post-Jump Questionnaire Landing Ratings

Variable	Sample size	Effect	df	Partial chi-square value	*p*-value
Rlandopn	n=29	Opinion	2	49.19	$p<.001$
		Jump height*Opinion	4	75.56	$p<.001$
		Legwear*Opinion	8	64.96	$p<.001$
Mobopn	n=29	Opinion	2	184.98	$p<.001$
		Legwear*Opinion	4	92.21	$p<.001$
Ilandopn	n=29	Opinion	2	32.14	$p<.001$
		Legwear*Opinion	6	59.45	$p<.001$
Rollopn	n=29	Opinion	2	36.11	$p<.001$
		Legwear*Opinion	4	16.90	$p<.01$

Soldiers' opinions about PLF performance, initial contact, mobility, and roll performance were not equally distributed among the three ratings. Fewer soldiers rated the overall PLF "harder" or initial landing contact as "more difficult." In addition, soldiers generally perceived that the braces lessened mobility, an opinion that may have been caused by the legwear's novelty. However, soldiers noted rolling and twisting performance to be little different from usual.

For all the opinion ratings, soldiers thought the different legwear conditions affected their landings, contact, mobility, and ability to roll. Paralleling the biomechanical data, the viscoelastic material landings were predominantly rated as "softer" or "easier" for overall PLF performance and initial contact. Surprisingly, soldiers thought the mobility and ability to roll afforded by ankle braces was "no different than usual," while the other brace combinations evoked greater "more difficult" responses. Differences in jump heights only affected the general PLF landing rating, Rlandopn: as jump height increased, the landing ratings moved to the "harder" designation.

In the post-study questionnaire, we asked the soldiers to review their performance and rank the legwear conditions for wear comfort, legwear support, and PLF posture aiding. In addition, soldiers made an overall ranking of the legwear. The responses for these rankings were mutually exclusive with a lower numerical ranking, indicating the legwear as "best" or beneficial. We used Friedman and Kendall's coefficient of concordance testing to evaluate the legwear rankings for significant differences and rater agreement.

The rankings for "leg support" and "aid to correct PLF posture" were not significantly different. Concerning "wear comfort," soldiers ranked the legwear as 1. boots, 2. ankle braces, 3. knee braces, and 4. ankle and knee braces together [$X^2(3, \underline{N}=26)=63.55, p<.001$]. Rankings of the overall performance were also statistically different, [$X^2(4, \underline{N}=26)=32.56$, $p<.001$]. See Table 19 for a summary of these rankings. The soldiers' order of preference (from best to worst) was viscoelastic padding, ankle braces, boots, knee braces, and ankle and knee braces worn together. Kendall's concordance testing of soldier's ranking orders revealed low agreement, $\underline{W}=0.30$, for the overall rankings and good agreement, $\underline{W}=0.80$ for "wear comfort" rankings. The overall ranking data supported the biomechanical findings of the efficacy of an attenuating device using impact-absorbing material.

Soldiers also evaluated 20 design features to determine the necessity of incorporation in new cushioning or bracing equipment. Ratings for each feature were tabulated as percentages (100% times the ratio of necessity category responses to total responses) across each necessity category. The ten highest rated features are shown in Figure 21. Soldiers identified the following features as the most important for a prototype design: easy to don, adjustable fit, portable and lightweight, and foot cushioning.

Table 19

Performance Ranking Averages by Legwear from Experiment I Post-Study Questionnaire

Legwear condition	Overall legwear ranking (n=27)	Wear comfort ranking (n=26)
Boots	2.6	1.1
Boots, ankle braces	2.5	2.2
Boots, knee braces	3.8	2.9
Boots, ankle and knee braces	4.1	3.9
Viscoelastic material	2.1	Na

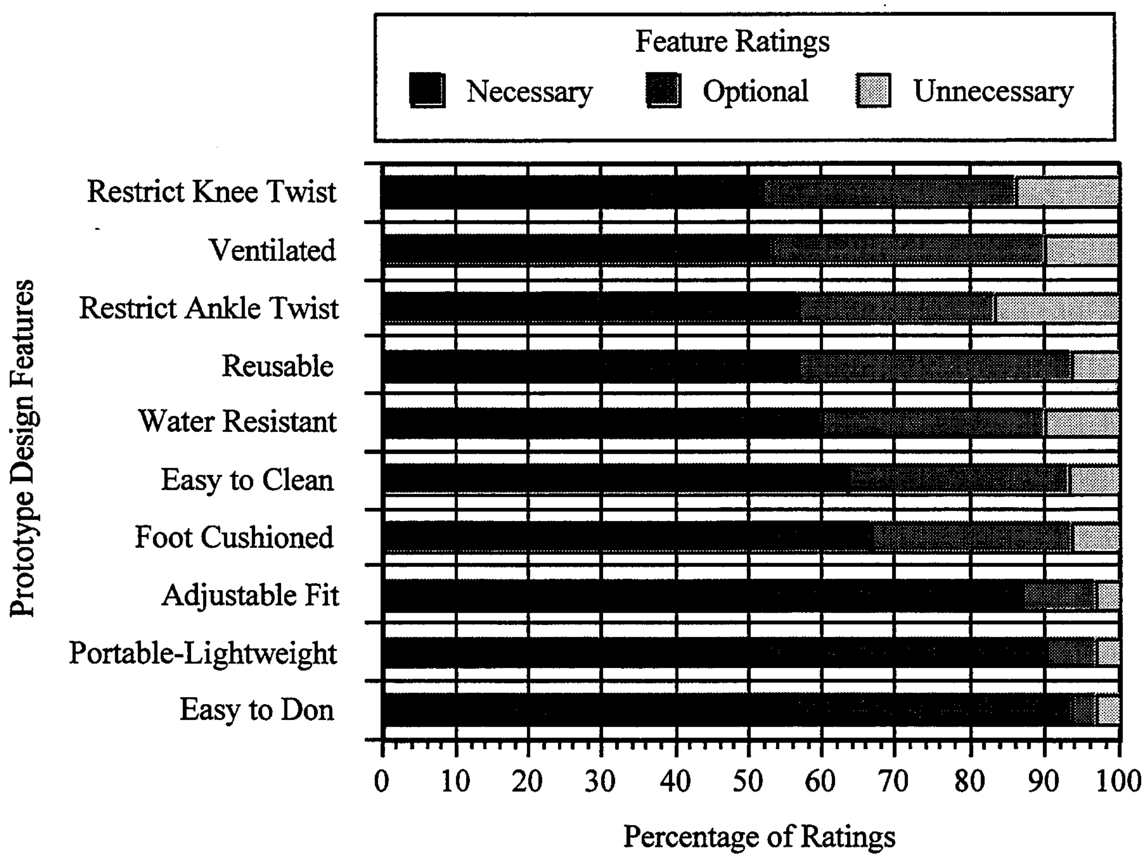

Figure 21. Experiment I: Ratings for the ten most preferred prototype design features.

Conclusions and Recommendations

Hypothesis Number 1

Based on data from the experiment, the hypothesis that there will be no difference in the results as a function of jump height is rejected with a few exceptions. In general, as jump height increases, impact forces, moments, impulses, and knee bend increase, while event times and ankle bend decrease. The most notable exception is that there is no statistically significant difference in the vertical force at the end of the reactive absorption phase (Fzend) as a function of jump height. This is because of the PLF technique. At the end of the reactive absorption phase, there is very little vertical movement, and the acceleration of the hip is approximately zero. Therefore, the vertical force is approximately equal to the test participant's body weight. Also, at this point in the PLF, the body is changing from vertical motion to horizontal motion as it twists and rolls to complete the PLF.

Other values that are not significantly different as a function of jump height are impulse from F2 to end, Frmaxtime, and moment at F1. Impulses from F2 to end are not significantly different because impulse is the integral of force over time, and as jump height increases, the vertical force increases while the time from F2 to end decreases. There is no significant difference in Frmaxtime, probably because the horizontal velocity for each jump was approximately the same. Therefore, it would take approximately the same amount of time to reach the maximum horizontal force for each jump. At F1, most of the motion in the PLF is in the vertical direction; there is very little twisting about the vertical axis at F1. Therefore, the moments at F1 are small for all jumps and not significantly different.

Hypothesis Number 2

Like the first hypothesis, the hypothesis that there will be no difference in the results as a function of legwear is rejected. The results of this experiment were significantly different as a function of legwear with a few exceptions. For most of the variables measured, legwear does affect the results. In general, jumps onto the viscoelastic material result in significantly lower vertical forces, horizontal forces, and moments than do jumps with the other legwear. The viscoelastic material also significantly increases the absorption times compared to the other legwear. For the viscoelastic material, the percent difference in vertical force and horizontal force is significantly lower than the percent differences for the other legwear conditions. The ankle braces worn alone or with the knee braces significantly decrease the amount of bending at the ankle compared to the other legwear, and the combination of the ankle and knee braces significantly decreases knee bend.

Of the variables measured, only four (Frend, Mzf1, Impf12, and Ckaf1) showed no significant differences as a function of legwear. Because of the PLF technique, the horizontal forces at the end of the reactive absorption phase are not significantly different. At this point in the PLF, test participants are translating vertical motion into horizontal motion, and it takes each individual approximately the same amount of horizontal force to twist and roll. As mentioned earlier, the moment at F1 is small and therefore not significantly different as a function of legwear. The impulse from F1 to F2 is not significantly different probably because the differences in forces and times between F1 and F2 for each legwear balance each other when the impulse is calculated. It is not surprising that there are no significant differences in knee angle at F1 because at this point in the PLF, most of the bending occurs at the ankles.

Hypothesis Number 3

Based upon the Pearson correlation coefficients, there are relationships between the biomechanical variables measured and the soldiers' weight, stature, and leg length. All of the significant relationships show a positive correlation with one exception. The change in knee angle at F1 (Ckaf1) is negatively correlated with weight, stature, and leg length. The change in knee angle at F1 may decrease as weight, stature, and leg length increase, so there can be more bend at the knees as the PLF progresses and the impact forces increase. In general, the relationship is that increasing weight, stature, and leg length results in increasing forces, moments, impulses, impact times, ankle bend, and knee bend.

Injury Prevention

In terms of injury prevention, the results of this experiment highlight the importance of keeping the impact velocity as low as possible. The average maximum vertical force for jumps from 1.07 m (3.5 ft), a descent velocity of approximately 4.57 m/s (15 ft/s), are one half the average maximum vertical force for jumps from 1.71 m (5.6 ft), a descent velocity of approximately 5.79 m/s (19 ft/s). Landings at lower descent velocities should result in a reduction in injuries because the forces that cause the injuries are lower.

Another reason to keep impact forces as low as possible is because long-term degenerative changes are also a concern for parachutists (Mustajoki, Nummi, & Meurman, 1978). Evidence shows that certain types of repeated loading on the joints can cause problems such as osteoarthritis (Radin et al., 1973). Reducing the impact forces in parachute jumping may also reduce degenerative changes to the joints of parachutists.

Use of Off-the-Shelf Braces

The legwear examined in this experiment was chosen for its potential to reduce injuries. The surprising result of this experiment is that the braces examined actually increased some of the impact forces. In particular, vertical and horizontal forces related to the injury mechanisms' torsion plus landing thrust and violent vertical fall were higher when the braces were worn than when only the boots were worn.

There are several reasons why wearing braces causes an increase in the forces. First, the braces restrict certain joint motions. Data from the experiment showed the ankle brace and the ankle brace-knee brace combination decreased ankle rotation in the sagittal plane. Also, the ankle brace-knee brace combination significantly decreased knee bend between F1 and F2 and from contact to F2. By restricting motion, a brace limits the amount muscles lengthen and thus the amount of kinetic energy the muscles absorb. If the muscles do not absorb the energy, the bones and ligaments must absorb it. Because they are stiffer than muscle, the resulting impact forces are higher.

Another reason braces increase impact forces is because braces somehow change the neuromuscular control of the lower extremities. Osternig and Robertson (1993) found significant changes in electromyographic activity in muscles that flex and extend the knee and ankle when a knee brace was worn by subjects running on a treadmill. The changes were mostly reductions in muscle activity.

One more reason braces increase impact forces may be because psychological factors are involved. Test participants may feel stiff when they wear the braces so they perform their PLFs stiffly, or they may rely on the braces instead of on their muscles to absorb the impact. Observations of the test participants, post-jump questionnaire responses, and comments from some test participants indicated that they felt stiff when wearing the braces. If they modified their PLFs, based on how they felt, their impact forces would increase. This result is similar to the result of the study by Dufek and Bates (1990), who found significantly higher forces for stiff landings. If test participants relied on the braces to absorb the impact rather than on their muscles, then, again, they modified their PLFs, which resulted in harder landings.

The knee braces examined in this experiment are not recommended for general use by paratroopers. Jumps with the knee braces result in force increases of 11.0% for maximum vertical impact force and 9.6% for maximum horizontal impact force compared to jumps in boots only. These force increases are the result of restricted motion, changes in neuromuscular control, psychological factors, or some combination thereof. An important drawback of the knee braces is the problem of discomfort. Test participants gave the knee braces low ratings for comfort, and because the straps holding the knee brace in place must be tight, it could be very uncomfortable to wear knee braces during a long flight before a parachute jump. Another problem with the knee braces is that they require soldiers to be trained to put them on properly.

This is not to say that knee braces are unacceptable in all situations. There may be situations when the chances of landing on an obstacle or very rough terrain are greater than landing on relatively smooth terrain. In that situation, it may be desirable to wear knee braces because they may offer some protection from lateral impacts.

Like the knee brace, the legwear condition that combined the ankle brace and the knee brace is not recommended for general use by paratroopers. This legwear condition resulted in the highest forces. It restricts motion more than the other legwear. It received the lowest comfort rating by the test participants, and because of the knee braces, it also has the problem of requiring soldiers to be trained to put them on properly.

It may be argued that training with the braces could potentially offset the negative effects of wearing a brace. Yet, in a study of a major college football team (Rovere, Haupt, & Yates, 1987) which required knee braces to be worn during all practices and games, the incidence rates of certain knee injuries were higher when the braces were worn than during a similar period when the braces were not worn. Therefore, emphasis should be placed on designing a protective device that does not have the problems associated with commercially available braces rather than trying to force paratroopers to adapt to items that are currently available.

Creation of a Data Base and Future Experiments

One of the most important accomplishments of this experiment is the creation of a data base of quantitative kinetic and kinematic measures of PLFs. These data can now be used by medical and scientific researchers studying the biomechanics of the lower extremities. Researchers can use the force, moment, and displacement data to examine such things as responses of individual bones and ligaments to PLFs. These data are also available for computer modeling. Results of simulations with models such as Jack (University of Pennsylvania, Philadelphia, Pennsylvania) and DYNAMAN (Air Force Materiel Command, Wright-Patterson Air Force Base, Ohio) can be verified with the results from this experiment. Using simulations, the computer model can be made to do PLFs during conditions that would be dangerous for test participants to attempt. For example, test participants could become needlessly injured if they took part in an experiment where they landed on very rough terrain or obstacles or landed at higher than normal speeds. These data can also be used as a guideline for human performance limitations. It can provide guidance about acceptable forces, moments, and displacements for PLFs or motions similar to the PLF.

The data collected in this experiment are valid for the laboratory conditions during which they were collected. In the future, an experiment to collect the same kinetic and kinematic data needs to be done in a field setting. If the results are the same for parachutists performing PLFs after jumping from an aircraft and landing on a drop zone, then future experiments can be conducted in the laboratory. This can save a considerable amount of time and money as devices are developed to prevent injuries to paratroopers.

Development of a Device to Prevent PLF Injuries

The legwear in this experiment that showed the greatest reduction in forces and moments when compared to the boots only condition was the viscoelastic material. In fact, jumps onto the viscoelastic material resulted in significantly lower forces than jumps in the other legwear. Therefore, the viscoelastic material shows promise as a material to be included in a device to reduce injuries to paratroopers. The viscoelastic material reduces the impact forces because it increases the time over which the impact is absorbed. The result, when considering vertical force, is that jumps onto the viscoelastic material from 1.71 m (5.6 ft) feel to the test participant like boots-only jumps from 1.52 m (5.0 ft).

Because ankle injuries comprise a large percentage of paratrooper injuries, the jump brace, or some means of ankle support, merits consideration for inclusion in a device to prevent injuries to paratroopers. Although the jump brace increases the maximum vertical impact force and the maximum horizontal impact force compared to the boots-only condition, it has been shown by Amoroso et al. (1994) to reduce the incidence of inversion and eversion ankle sprains. Also, in terms of comfort, the jump brace was rated second to boots by the test participants.

Based on the results of this experiment, it is recommended that impact-absorbing material such as the viscoelastic material be used in a device to prevent injuries. Because the forces and moments that cause injuries to paratroopers start at the point of contact and are transmitted up the body, the impact-absorbing material should be on or in the soles of the paratrooper's boots. Developing a device to go on or in the bottom of the paratrooper's boots can then be the base to which structures that support and protect the ankle, knee, and hip are attached. Integrating all these into one unit will then provide a complete lower extremity protective device.

EXPERIMENT II

Method

Experimental Design

This experiment was based on the successful reduction of impact forces and moments by the viscoelastic material in Experiment I. It was conducted from 21 September to 22 October 1993 to examine the efficacy of impact-absorbing soles attached to paratroopers' boots. Experiment II was also a repeated measures (within subject) design. Twenty-four test participants took part in this experiment. None of the test participants in this experiment had participated in Experiment I. The legwear and jump heights are shown in the test matrix in Table 20. Each test participant jumped in each legwear from each height. The treatment order was randomized to minimize order effects. Each test participant made 12 jumps. The data were collected during two sessions. Test participants made three to nine jumps per session, depending upon travel and testing schedules. All of the test participants performed right-side PLFs.

Table 20

Test Matrix Experiment II

Legwear condition	Test participants per jump height Jump height 1.37 m (4.5 ft)	 1.71 m (5.6 ft)
Boots	24	24
Boots, ankle braces	24	24
Boots, ankle braces, poron soles	24	24
Boots, ankle braces, EVA[a] soles	24	24
Boots, ankle braces, poron + sorbothane soles	24	24
Boots, ankle braces, poron + akton soles	24	24

[a]EVA = ethylene vinyl acetate

Test Participants

The test participants in this experiment were active duty SOF soldiers. All of the test participants were airborne qualified males on jump status. No one on medical profile was allowed to participate. Each test participant's medical history was reviewed by an Army doctor before he was allowed to participate. The Human Use and Experimental Design Panel of ARL approved the protocol for the experiment. Before taking part, test participants received a full explanation of the experiment. Each test participant read and signed a volunteer consent agreement.

Apparatus

Like Experiment I, this experiment was conducted in an indoor laboratory. The apparatus used in this experiment was the same as that used in Experiment I with a few exceptions. The knee braces were not used in this experiment, and the force plate was not covered with viscoelastic material for any of the test cells. The following apparatus, not used in Experiment I, was used in this experiment:

Boots and Uniforms - In this experiment, test participants wore their own battle dress uniforms and boots.

Ankle Braces - The jump brace (02G) (used in Experiment I) and the jump brace (02H), from Aircast, Inc., were both used in this experiment. The jump brace (02H) was developed between the time of Experiment I and Experiment II. Aircast, Inc., designed it for paratroopers whose boots are size 11 or larger. The jump brace was worn on the outside of the boot.

Additional Equipment - To make the jumps more realistic, test participants also wore some of the equipment they would have worn for a normal jump. The additional equipment included a parachute harness, load-bearing equipment, a reserve parachute, a full canteen, and two M16 ammunition pouches full of simulated ammunition. This additional equipment weighed 13.6 kg (30 lb) (see Figure 22).

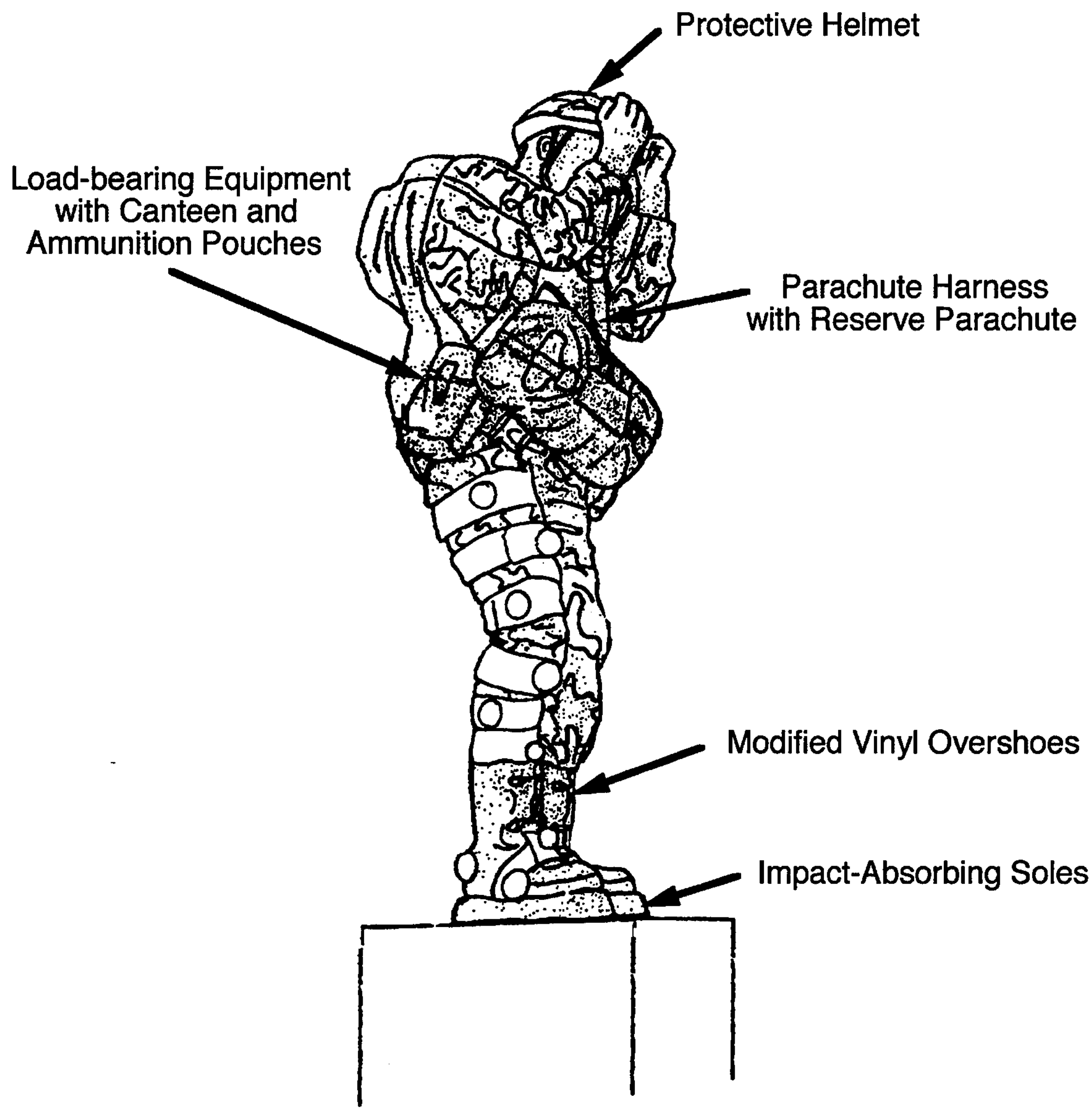

Figure 22. Test participant wearing additional equipment.

Impact-Absorbing Soles - The impact-absorbing soles were created by HRED of ARL. All the soles were 3.81 cm (1.5 in.) thick, the same thickness as the viscoelastic material used in Experiment I. The shape of the soles was generated by tracing the outline of a size 10-1/2 wide hot weather boot inserted into a size 8 vinyl overshoe. The pattern was modified slightly by making the inside edge straight and smoothing the outside curves. The impact-absorbing soles were given a 15° outward taper except along the inside edge, which was kept straight. A wide strip of loop-side velcro with a pressure-sensitive adhesive backing was placed on top of the impact-absorbing sole. Four different kinds of impact-absorbing soles were evaluated in the experiment. Some of the properties of the soles are given in Table 21.

Table 21

Material Properties

	Impact-absorbing soles			
	Poron	EVA	Sorbothane with (poron)	Akton with (poron)
Material type	High density open cell urethane foam	Microcellular EVA closed cell foam	Viscoelastic plasticized polyurethane polymer	Viscoelastic urethane rubber polymer
Hardness	Shore "0" 18	Shore "a" 25-30	Shore "00" 30	Shore "000" 45
Weight of soles per pair	0.86 kg (1.89 lb)	0.51 kg (1.12 lb)	1.21 kg (2.66 lb)	1.14 kg (2.51 lb)
Optimum temperature performance range	-40 - 70° C (-40 - 158° F)	-57 - 71° C (-70 - 160° F)	-40 - 93° C (-40 - 200° F)	-54 - 104° C (-65 - 220° F)

The materials for the soles were chosen based upon recommendations of the Materials Directorate of ARL: availability, suitability for the environment, and commercial use in similar applications. The first sole was Poron® (Rodgers Corporation, East Woodstock, Connecticut), a high density, open cell, urethane foam. The second sole was Royal A-II EVA (The Biltrite Corporation, Waltham, Massachusetts), a polyethylene foam. Figure 23 shows some of the dimensions of the Poron and EVA soles. In the third and fourth soles, viscoelastic materials were sandwiched between layers of Poron foam. The third sole consisted of Sorbothane and Poron (Sorbothane soles). The fourth sole consisted of Akton® (Action Products, Inc., Hagerstown, Maryland) and Poron (Akton soles). Figure 24 shows some of the dimensions of the Sorbothane soles and the Akton soles. Sorbothane and Akton were embedded in Poron to provide lightweight, stable soles. Soles made entirely of Sorbothane or Akton were too heavy to allow a proper PLF and so soft that they made walking difficult.

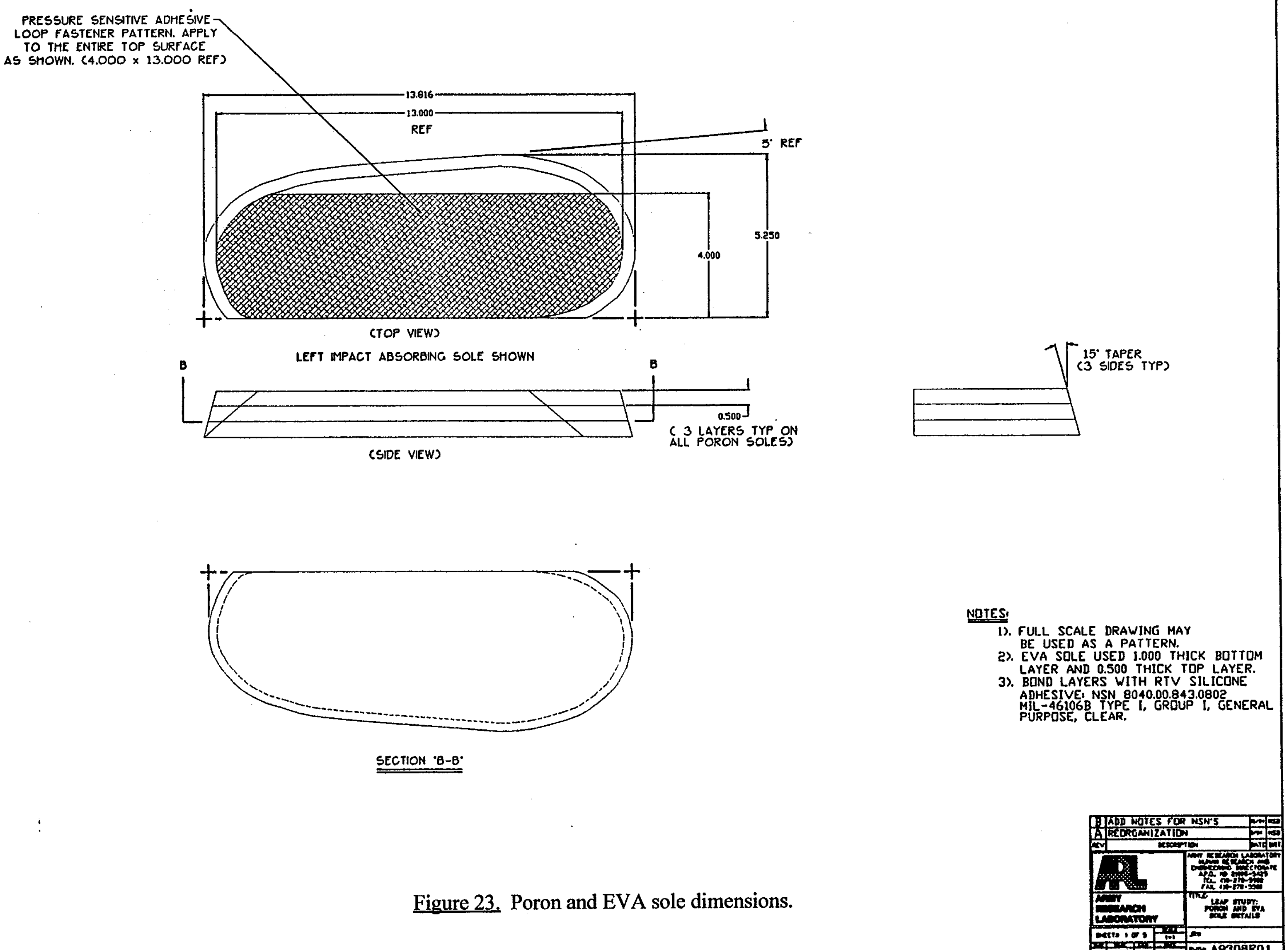

Figure 23. Poron and EVA sole dimensions.

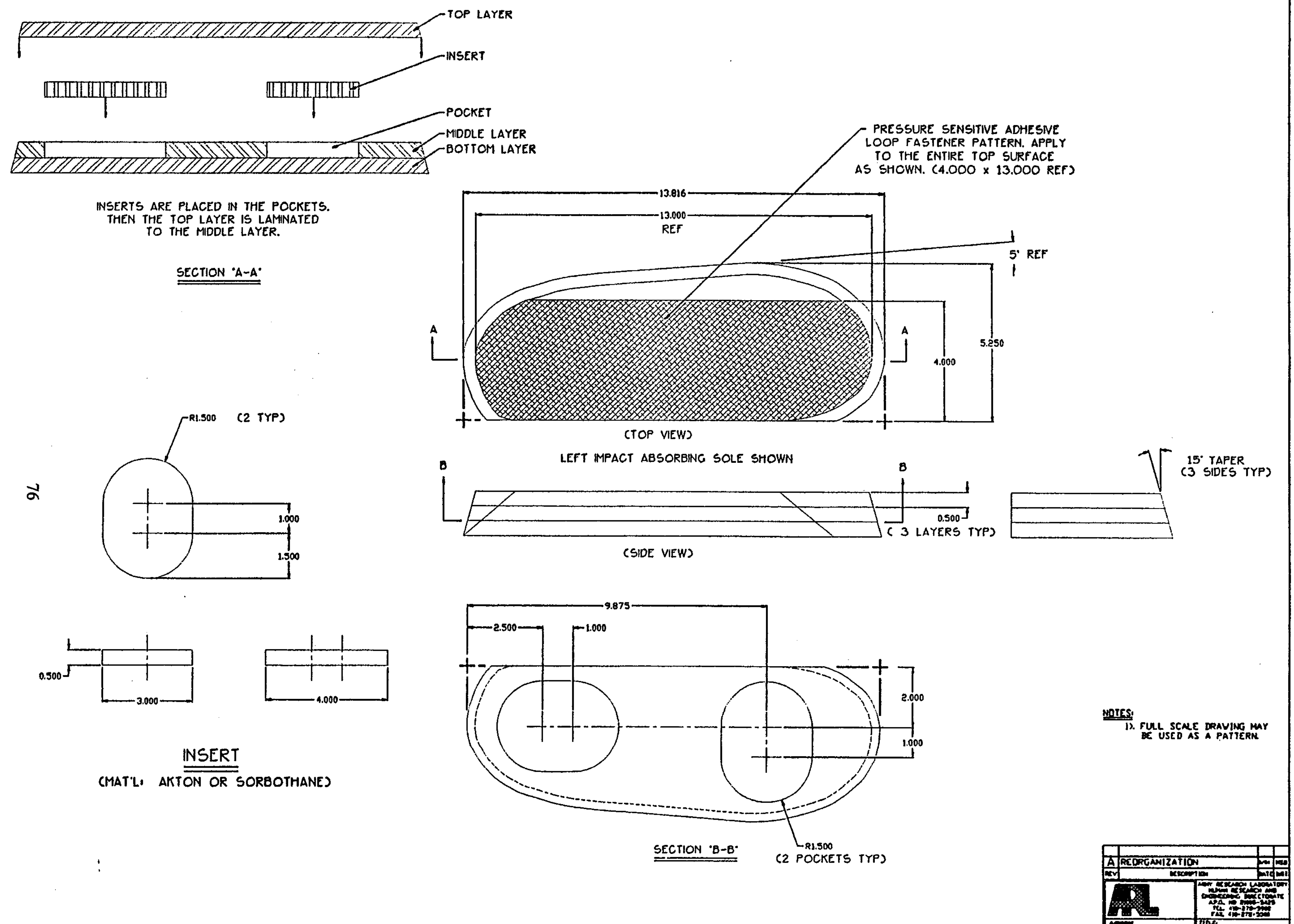

Figure 24. Sorbothane and Akton sole dimensions.

The Poron soles were constructed by laminating three 1.27-cm (0.5-in.) thick pieces together to produce a 3.81-cm (1.5-in.) thick sole. Some of the layers of the Poron sole were bonded with acrylic pressure-sensitive adhesive sheets. Other layers were bonded with room temperature vulcanizing (RTV) silicone adhesive after being degreased.

The EVA soles were constructed by bonding 2.54-cm (1-in.) and 1.27-cm (0.5-in.) thick pieces of EVA together. All surfaces were degreased before bonding with RTV silicone adhesive.

The Sorbothane soles were constructed by inserting 1.27-cm (0.5-in.) thick ovals of Sorbothane into forefoot and heel pockets cut from the middle layers of pairs of Poron soles. The Akton soles were constructed by inserting 1.27-cm (0.5-in.) thick ovals of Akton into forefoot and heel pockets cut from the middle layers of pairs of Poron soles. Section A-A in Figure 24 shows a cross section of the Sorbothane soles and the Akton soles. These soles were laminated using the same methods used to construct the Poron soles.

Modified Overshoes - Olive green, vinyl overshoes were modified, as shown in Figure 25, so the impact-absorbing soles could be easily put on and taken off during the experiment. A 0.32-cm (0.125-in.) thick layer of RTV silicone adhesive was used to bond hook-side velcro to the forefoot and heel sections of the overshoes. Aluminum rivets (0.32-cm diameter) were also used to secure the velcro to the overshoes. Depending upon the size of the overshoes, eight to ten rivets were used in the forefoot, and five to six rivets were used in the heel.

Procedure

Warm-Up

The same warm-up procedure used in Experiment I was used in this experiment.

Anthropometry

The same anthropometry procedure used in Experiment I was used in this experiment.

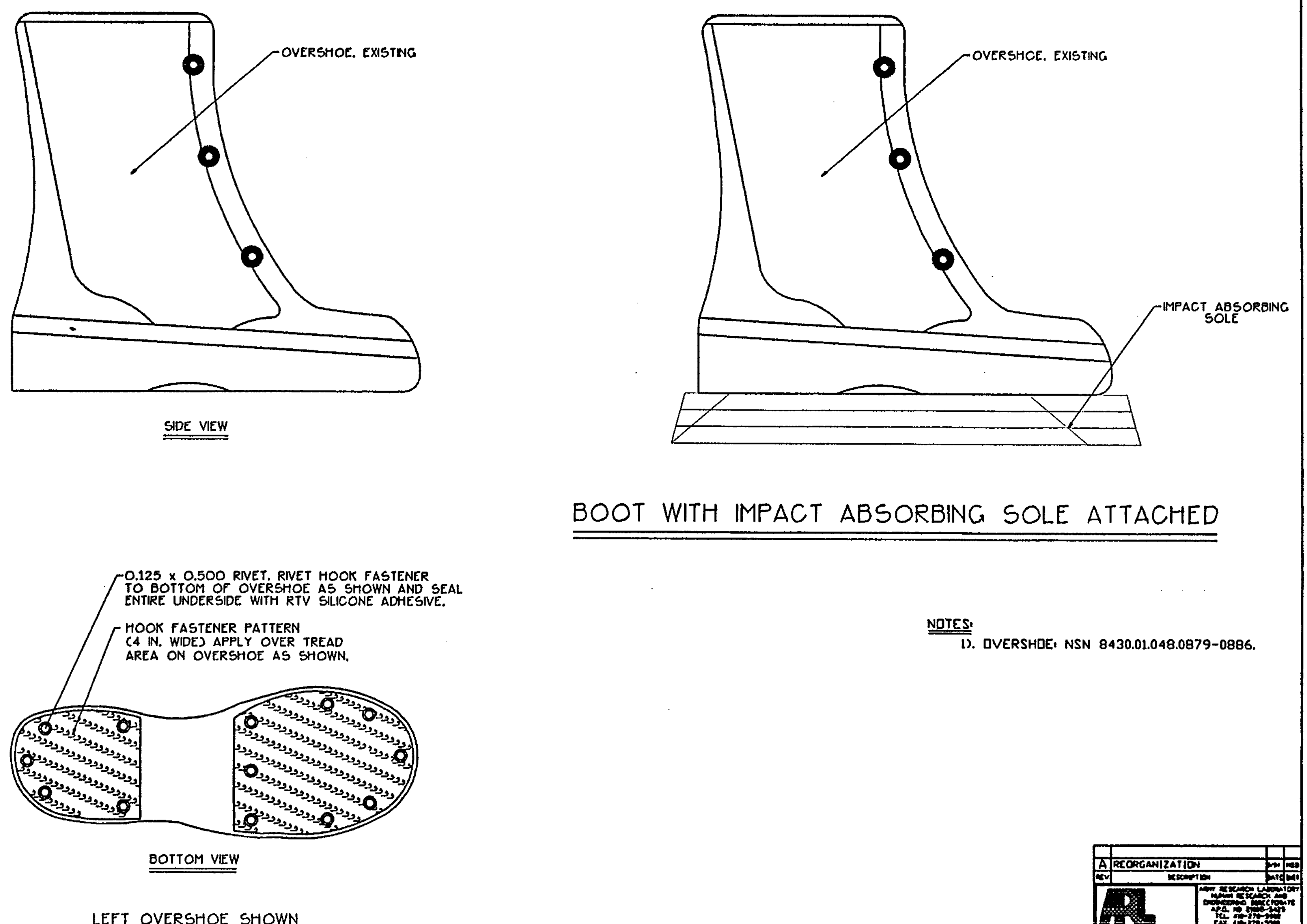

Figure 25. Modified overshoe with impact-absorbing sole.

Fitting the Impact-Absorbing Soles

Test participants were fitted with vinyl overshoes one or two sizes smaller than their boot size. This was done to ensure a snug fit and to eliminate motion between the soldier's boots and the overshoes. The impact-absorbing soles were attached to the velcro on the bottom of the overshoes by aligning the inside (straight) edge of the impact-absorbing sole with the inside edge of the overshoe and aligning the heel of the impact-absorbing sole with the heel of the overshoe. To ensure that the impact-absorbing soles were always attached in this manner, members of the team conducting the experiment always put the impact-absorbing soles on the test participants.

In this experiment, test participants wore ankle braces with the impact-absorbing soles. This was done for several reasons. Ankle protection needs to be incorporated in a device to prevent lower extremity injuries because ankle injuries are the most common lower extremity injuries occurring among parachutists (Ciccone & Richman, 1948; Essex-Lopresti, 1946; Hallel & Naggan, 1975; Kirby, 1974; Neel, 1951). The study by Amoroso et al. (1994) found a statistically significant decrease in the number of inversion and eversion ankle sprains for soldiers wearing the jump brace during Airborne School at Ft. Benning. The jump brace is now being used by all students at the Airborne School. Feedback from the test participants in Experiment I indicated that paratroopers saw a need for and would wear ankle braces. Finally, safety was also a consideration. Test participants, unaccustomed to the 3.81-cm thick impact-absorbing soles, could possibly injure themselves when wearing this unfamiliar footwear.

Placing the Markers

The marker placement procedure used in Experiment I was used for this experiment.

Measuring the Marker Locations

The same procedure used to measure the marker locations in Experiment I was used in this experiment.

Data Collection

The data collection procedure used in Experiment I was used for this experiment except for slight changes in the post-jump questionnaire and post-study questionnaire. These changes were necessary because different legwear was tested in this experiment (see Appendices E and F).

Data Processing

The same procedure for data processing used in Experiment I was used in this experiment.

Results and Discussion

Experiment II

In Experiment I, we determined that the viscoelastic material approach is superior for reducing ground reaction forces and moments during soldiers' PLFs. Therefore, we employed this material approach into the design of absorption sole prototypes and tested their impact mitigation effects in a second experiment.

Experiment II examined a null hypothesis about the soles' performance: there will be no difference in the results for jumps from the same height as a function of the cushioning material attached to the test participants' boots. As indicated by the experimental matrix in Table 20, soldiers completed PLFs from two jump heights, 1.37 m (4.5 ft) and 1.71 m (5.6 ft), and wore six different legwear combinations. These legwear conditions included combat boots only (boots); combat boots with ankle braces (ankle braces); combat boots, ankle braces, and Akton-Poron material soles (Akton soles); combat boots, ankle braces, and EVA material soles (EVA soles); combat boots, ankle braces, and Poron material soles (Poron soles); and combat boots, ankle braces, and Sorbothane-Poron material soles (Sorbothane soles). Note that the paratroopers wore ankle braces with and without the absorption soles. Other paratrooper studies established the ankle braces' ability to reduce injury. We wanted to determine if the ankle braces augmented the soles' performances. The soldiers' 12 jumps allowed a repeated measures approach for the experimental design.

During each PLF, we measured ground reaction forces, vertical moments, vertical impulses, knee and ankle angle changes, and absorption times for the contact, F1 impact, F2 impact, and end events of the reactive landing phase. These PLF measures were derived in Experiment I after examination of the baseline biomechanical data.

As in Experiment I, within-subjects ANOVAs were performed on each biomechanical measure. In addition, soldiers provided subjective feedback using post-jump and post-study questionnaires. Nonparametric statistics evaluated this feedback: hierarchical loglinear analysis modeled the performance ratings on the post-jump surveys, and chi-square tests determined soldier equipment preferences.

Stature, Weight, and Leg Length Correlations with PLF Performance

Correlational analysis was used to examine the relationship between soldiers' weight, stature, and leg length and the biomechanical measures of PLF performance. Table 22 reveals the significant Pearson product-moment results for the correlational analyses.

Pearson product-moments indicated that soldiers' weights were significantly correlated to many measures of force, impulse, impact times, ankle bend, and knee bend. For all these correlations, an increase in a soldier's weight was accompanied by a proportional increase in the performance measurement. Surprisingly, only the moment at heel touchdown was significantly related to weight. Forces at the later portion of the reactive landing period did not seem to be highly correlated with soldier weight.

Stature had few significant correlations with the biomechanical variables: maximum vertical impact (Fzmax); force and impulse measurements at toe and heel touchdown (Fzf1, Fzf2, Impf1, Impf12, and Impf2); the vertical moments at maximum vertical and horizontal impacts (Mzfzmax and Mzfrmax); the change in ankle angle between F1 and F2 impacts (Caaf12); and the horizontal force at the end of reactive absorption (Frend). Generally, larger stature produced increased values of these measures, while the moment measures (Mzfzmax, Mzfrmax, and Mzf2) and the time between F2 impact and end of reactive absorption (F2endtime) decreased.

Since soldiers' stature is highly correlated with leg length, we expected similar Pearson product-moment results for the leg length and performance measures' correlations. However, leg length was significantly correlated with more biomechanical measures. All impact time and impulse measurements increased proportionally with leg length. Ankle bend (Caaf12 and Caaf2) and force values also had significant positive correlation coefficients. Again, horizontal impact at the end of reactive absorption (Frend) decreased with larger leg lengths.

Table 22

Experiment II: Pearson Correlation Coefficients Between Soldiers' Weights, Statures, and Leg Lengths and Selected PLF Biomechanical Variables

	Biomechanical variable	Weight	Stature	Leg length	Sample size[a]
Forces	Fzmax	.18**	.19**	.11*	23
	Frmxz	.18**	.09	.31**	23
	Frmax	.13*	.07	.10	21
	Fzmxr	.21**	.20**	.35**	21
	Fzf1	.33**	.30**	.21**	21
	Fzf2	.10*	.18**	.11	21
	Frf2	.11	.08	.31**	21
	Frend	-.04	-.13*	-.18**	23
	Mzfzmax	.07	-.14*	.08	17
	Mzfrmax	.06	-.16*	.06	17
	Mzf2	.07*	-.15*	.07	16
Impulses	Impf1	.33**	.14*	.27**	21
	Impf12	.40**	.23**	.45**	21
	Impf2	.44**	.23**	.46**	21
	Impf2end	.27**	.02	.38**	21
Impact times	Frmaxtime	.22**	.04	.21**	21
	F1time	.25**	.02	.18**	21
	F2time	.24**	.03	.26**	21
	F12time	.18*	.03	.25**	21
	F2endtime	.01	-.18**	.17**	21
	Totaltime	.12*	-.12	.23**	23
Ankle bend	Caaf1	.29**	-.04	.04	18
	Caaf12	.12	.18**	.18**	18
	Caaf2	.32**	.13	.18**	18
Knee bend	Ckaf1	.25**	- .01	.03	18
	Ckaf2	.17*	- .03	.09	18

**α<.01 significance level. *α<.05 significance level. [a]Sample sizes for correlational analysis also used in later ANOVAs.

Examination of Jump Height and Legwear Effects on PLF Performance

Evaluation of the experimental hypothesis through a repeated measures study design considered the two main effects of jump height and legwear along with their interaction. A 0.05 significance level was employed thoughout the ANOVAs and post hoc testing. As in Experiment I, we checked the homogeneity of variance assumption for the ANOVA calculations and employed Greenhouse-Geiser corrections as necessary. When appropriate, we used post hoc testing to further examine differences among the biomechanical measures. Because of soldier performance and data collection limitations, sample sizes for the ANOVA and nonparametric statistics ranged from n=24 to n=15.

Forces

Since the viscoelastic material was so successful in reducing impact forces during the PLF, we believed the force measures would indicate the usefulness of absorption soles to lessen impact effects. In addition, the large magnitude of the PLF impact forces should delineate the performances of the four damping materials used in the soles. The force measures included the vertical and horizontal resultant ground reaction forces present at maximum levels, and the F1, F2, and end events of the reactive landing phase. Table 23 indicates the ANOVA results for these force measures.

Besides determining the statistically significant differences among these forces' results, we also noted whether biomechanically meaningful differences existed between the absorption soles' performances. According to Bates (1989), even though statistically significant differences may not be seen in force results, researchers should consider meaningful differences when examining equipment and injury mechanisms. We used Bates' (1989) benchmark of 100 N to determine the presence of biomechanically meaningful differences.

The higher descent velocities produce greater impact effects, which a paratrooper must endure during his PLFs. ANOVA results in Table 23 confirmed this relationship. Jump height elevation from 1.37 m to 1.71 m caused statistically significant increases in most of the ground reaction force measures: maximum impact events Fzmax and Frmax along with the accompanying horizontal and vertical forces, Frmxz and Fzmxr; toe touchdown at F1 impact; and heel contact at F2 impact. As jump height rose, force differences ranged from 234 N to 2427 N--10.8% to 30.1% increases.

Table 23

Experiment II: ANOVA Results for Vertical and Horizontal Resultant Forces

Variable	Effect	F-ratio	*p*-value
Fzmax	Jump height	F(1,22)=126.12	*p*<.001
	Legwear	F(5,18)= 20.45	*p*<.001
	Jump height x legwear	F(5,18)= 7.49	*p*<.01
Frmxz	Jump height	F(1,22)= 10.27	*p*<.01
	Legwear	F(5,18)= 6.07	*p*<.01
	Jump height x legwear	F(5,18)= 7.62	*p*<.01
Frmax	Jump height	F(1,20)= 82.77	*p*<.001
	Legwear	F(5,16)= 11.55	*p*<.001
	Jump height x legwear	F(5,16)= 1.94	ns
Fzmxr	Jump height	F(1,20)= 30.90	*p*<.001
	Legwear	F(5,16)= 5.54	*p*<.01
	Jump height x legwear	F(5,16)= 3.17	*p*<.05
Fzf1	Jump height	F(1,20)= 72.21	*p*<.001
	Legwear	F(5,16)= 3.52	*p*<.05
	Jump height x legwear	F(5,16)= 3.94	*p*<.05
Frf1	Jump height	F(1,20)= 55.24	*p*<.001
	Legwear	F(5,16)= 1.19	ns
	Jump height x legwear	F(5,16)= 1.03	ns
Fzf2	Jump height	F(1,20)=155.08	*p*<.001
	Legwear	F(5,16)= 19.91	*p*<.001
	Jump height x legwear	F(5,16)= 7.17	*p*<.01
Frf2	Jump height	F(1,20)= 10.48	*p*<.01
	Legwear	F(5,16)= 9.04	*p*<.001
	Jump height x legwear	F(5,16)= 5.21	*p*<.01
Fzend	Jump height	F(1,22)= 0.07	ns
	Legwear	F(5,18)= 16.99	*p*<.001
	Jump height x legwear	F(5,18)= 0.31	ns
Frend	Jump height	F(1,22)= 0.32	ns
	Legwear	F(5,18)= 1.34	ns
	Jump height x legwear	F(5,18)= 2.56	ns

Maximum Vertical Impact (Fzmax)

At maximum vertical impact, soldiers' Fzmax results indicated an interaction between jump height and legwear conditions (see Table 23). Examination of Figure 26 reveals that this interaction occurred for landings with the absorption soles made of EVA and Sorbothane materials. Fzmax forces ranged from 6883 N (8.9 times a soldier's body weight) to 14040 N (18.1 times body weight). Among the soles, EVA produced the highest Fzmax results at the 1.37-m jump height and the lowest forces at 1.71 m. Conversely, the Sorbothane soles caused low Fzmax results at 1.37 m and the largest force effect at 1.71 m. Basically, these force absorption performances by the soles diverged at the higher jump height.

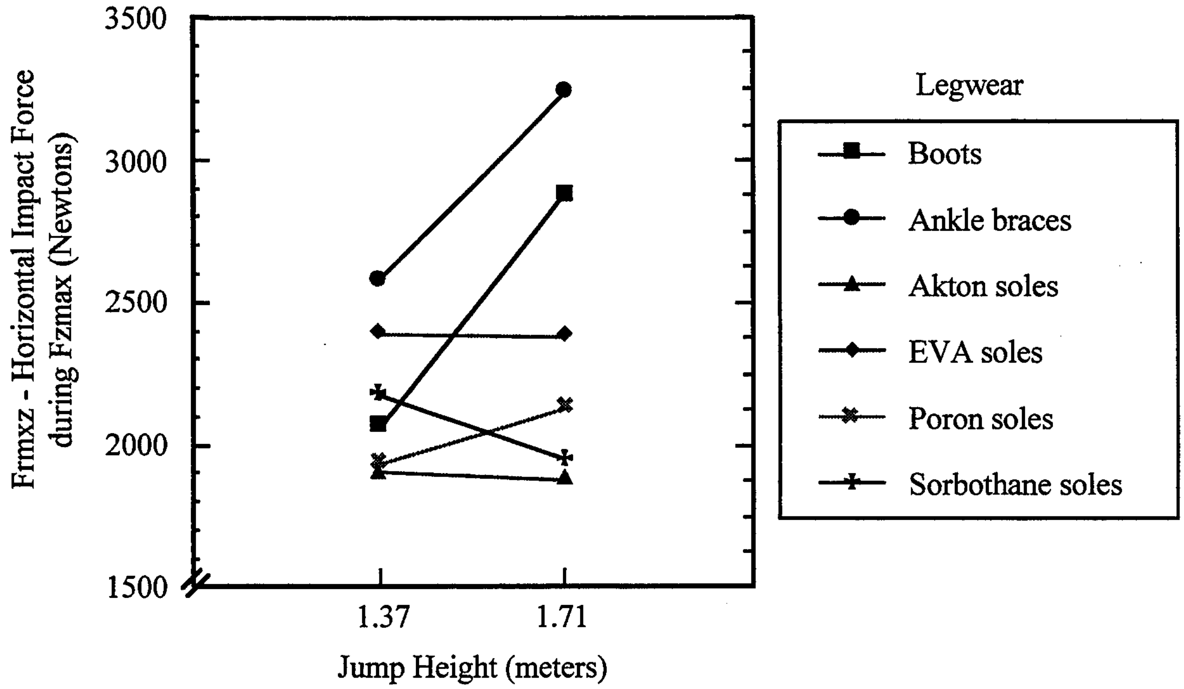

Figure 26. Experiment II: Maximum vertical impact force versus jump height by legwear.

Table 23 also indicates that the main effect of legwear caused significant differences in the Fzmax forces. All of the absorption soles greatly reduced the maximum vertical impact over the boots and ankle braces conditions. However, post hoc testing did not establish any significant differences between the absorption materials. As expected, the ankle braces caused the highest Fzmax impact, 12151 N, followed by the boots-only condition, 10213 N. The EVA soles had the lowest Fzmax average at 7945 N, which was more than 100 N less than the force averages of the Sorbothane and Akton soles.

Resultant Force During Maximum Vertical Impact (Frmxz)

The horizontal resultant forces accompanying the maximum vertical impact event, Frmxz, also exhibited significant interaction between jump height and legwear conditions (see Table 23). When soldiers wore the Akton and EVA soles, they experienced relatively consistent Frmxz levels of 1900 N and 2400 N, respectively. Frmxz results for the Sorbothane soles decreased more than 10% as jump height increased. Figure 27 shows that the EVA and Sorbothane soles produced higher Fzmxr forces at the 1.37-m jump height. These results did not parallel the soles' performances for Fzmax.

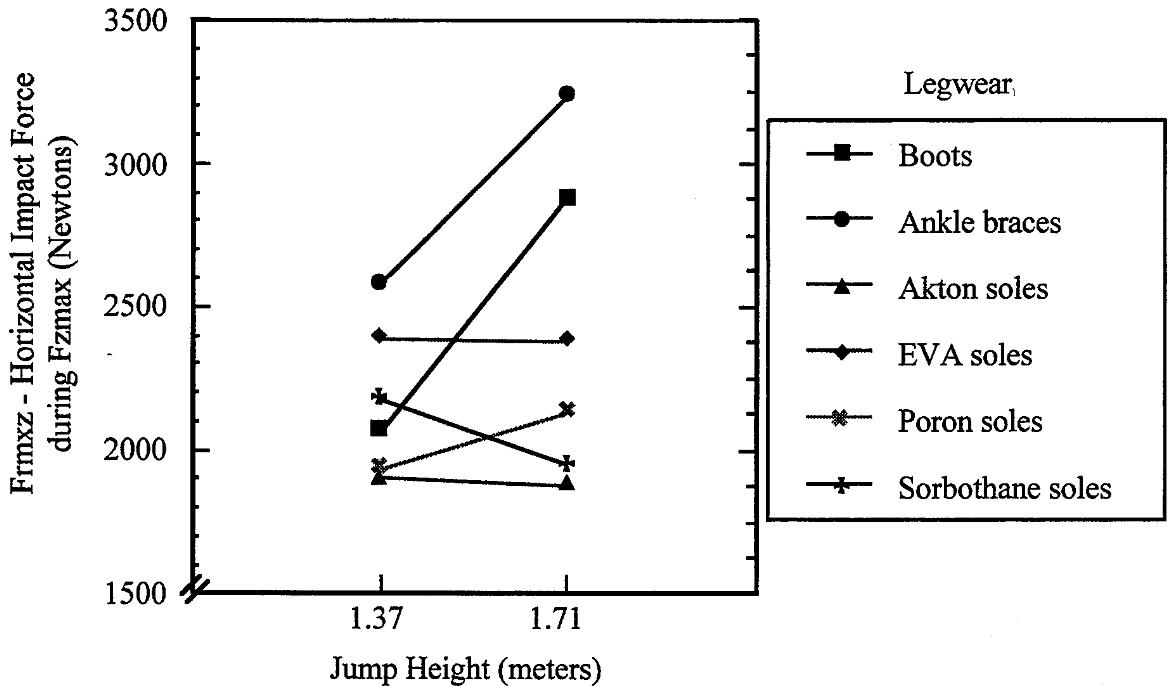

Figure 27. Experiment II: Horizontal impact force at maximum vertical impact versus jump height by legwear.

Examination of Frmxz results by legwear approach also revealed significant differences. The highest Frmxz averages were produced by the boots and ankle braces approaches, 2472 N and 2910 N (3.3 and 3.8 times body weight, respectively). Wearing the Akton, Poron, or Sorbothane soles afforded significant force reductions compared to the ankle braces condition. Only the Akton soles could significantly lower the Fzmxr forces with respect to landing in boots only. Yet, all the soles did offer at least a 100-N reduction over the boots-only approach. Biomechanically meaningful differences did exist between the damping soles

Fzmxr results since the EVA material averaged 300 N higher than the Sorbothane and Poron, and 500 N greater than Akton.

Maximum Horizontal Impact (Frmax)

Generally, the maximum horizontal resultant force, Frmax, occurred after heel contact. This late occurrence may be attributable to the paratrooper making a stabilizing correction as a response to the soles' configuration: velcro attachment to the overboot and lack of indentation at the ball of the foot. Table 23 indicates that the variation of legwear condition produced significant differences in Frmax forces. These forces averaged 2881 N (3.8 times a paratrooper's body weight) to 3842 N (5.1 times body weight). According to Figure 28, the soles had lower Frmax averages than the boots-only or ankle braces conditions. However, this reduction was only statistically significant with regard to the ankle braces. Scheffé testing revealed no significant differences between the soles Frmax results, yet the Akton soles averaged 100 N less than the other material approaches.

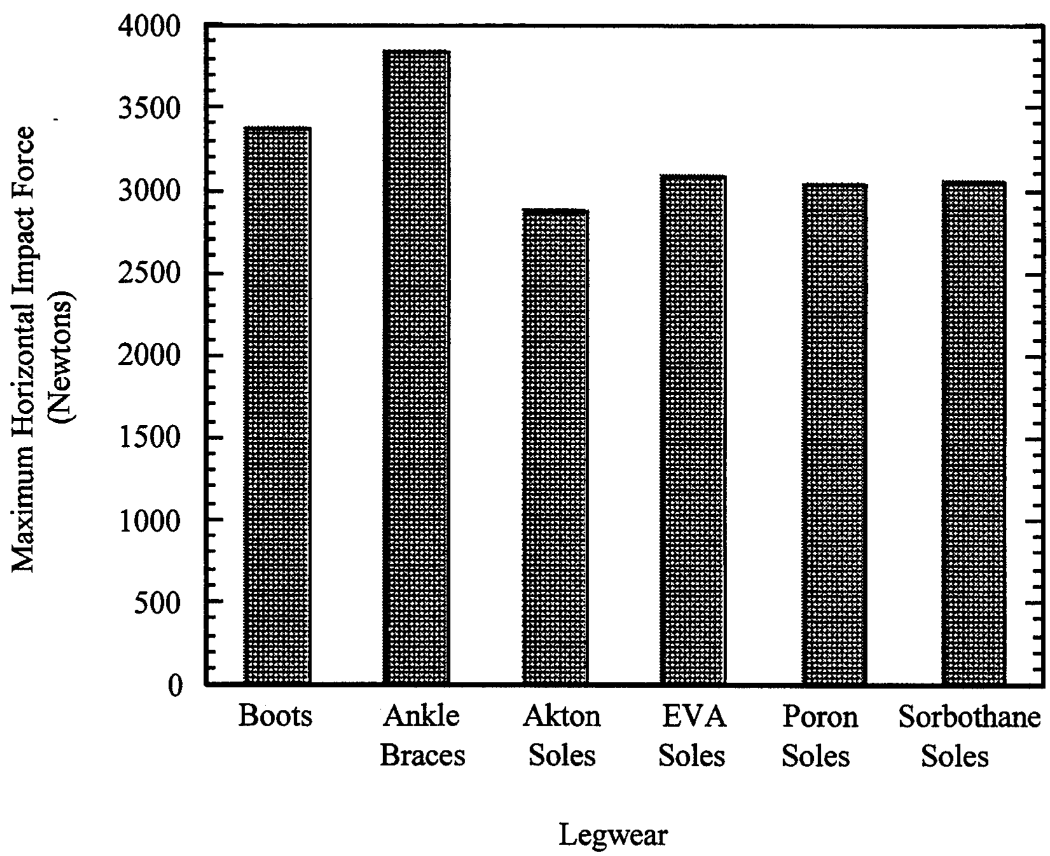

Figure 28. Experiment II: Maximum horizontal impact force by legwear.

Vertical Force during Maximum Horizontal Impact (Fzmxr)

ANOVA results for Fzmxr, the vertical force occurring at the Frmax event, reveal both jump height-legwear interaction and legwear main effects (see Table 23). As shown in Figure 29, the interaction effect can be attributed by the performances of the absorption soles. Fzmxr results for the EVA and Poron soles diverge as jump height increases from 1.37 m to 1.71 m. Elevation of jump height caused the soles' Fzmxr forces to increase only 500 N to 1000 N, while landings in the ankle braces or boots averaged 1500 N to 2000 N increases. The Fzmxr forces averaged 5507 N to 9252 N.

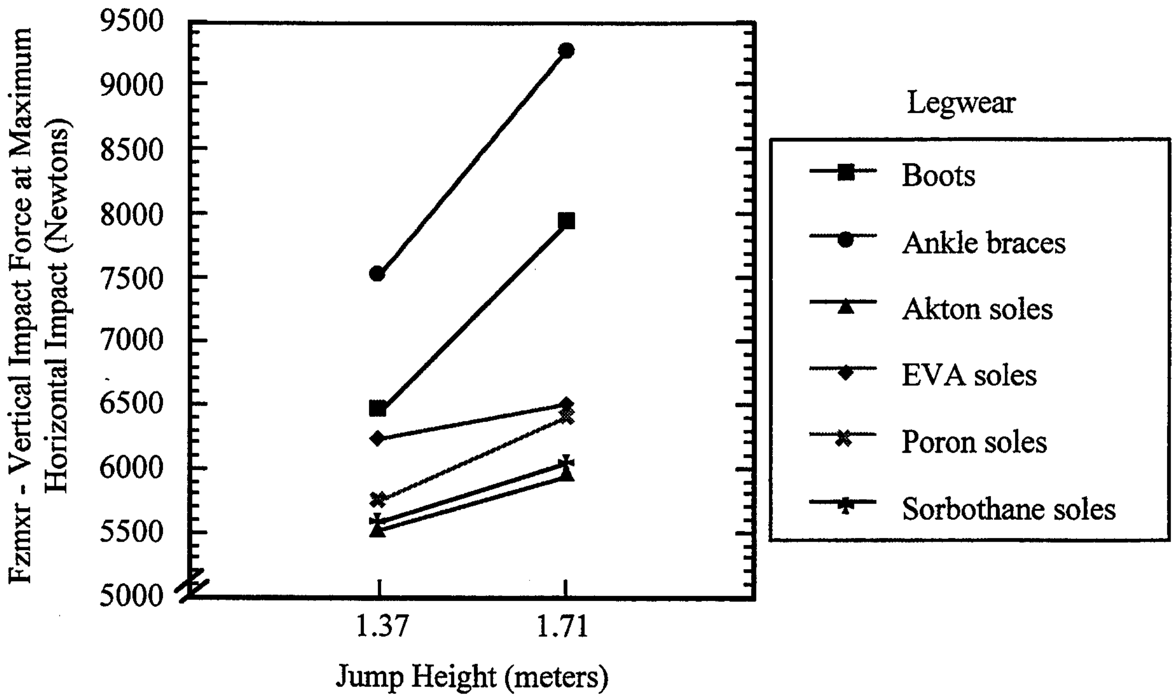

Figure 29. Experiment II: Vertical impact force during maximum horizontal impact versus jump height by legwear.

Paralleling Frmax results, the soles offered at least a 100-N reduction in Fzmxr forces when compared to boots-only and ankle braces performances. Again, this reduction was significant with respect to ankle braces landings. Using Bates' (1989) definition of a biomechanically meaningful difference, we determined that the Akton and Sorbothane soles offered improvement in vertical force absorption over the EVA and Poron soles.

Vertical Force at Toe Touchdown (Fzf1)

At the F1 impact event produced by toe touchdown, statistically significant differences existed between the vertical force results. As indicated in Table 23, these differences were caused by variation of legwear approach and the interaction between jump height and legwear conditions. Increasing jump height caused a divergence of Fzfl forces for the boots and ankle braces landings from 5000 N at 1.37 m to 5700 N and 6500 N, respectively, at 1.71 m. In Figure 30, the jump height-legwear interaction is also evident as the Sorbothane soles' force absorption worsened with jump height elevation compared to the other soles' Fzfl results.

Surprisingly, soldiers' landings in the boots-only condition produced the highest Fzfl impact of 5752 N (7.3 times body weight). All the soles offered significant reductions, 380 N to 900 N, with respect to the boots landings. Wearing EVA or Poron soles provided a 100-N reduction in Fzfl as opposed to the Akton or Sorbothane soles.

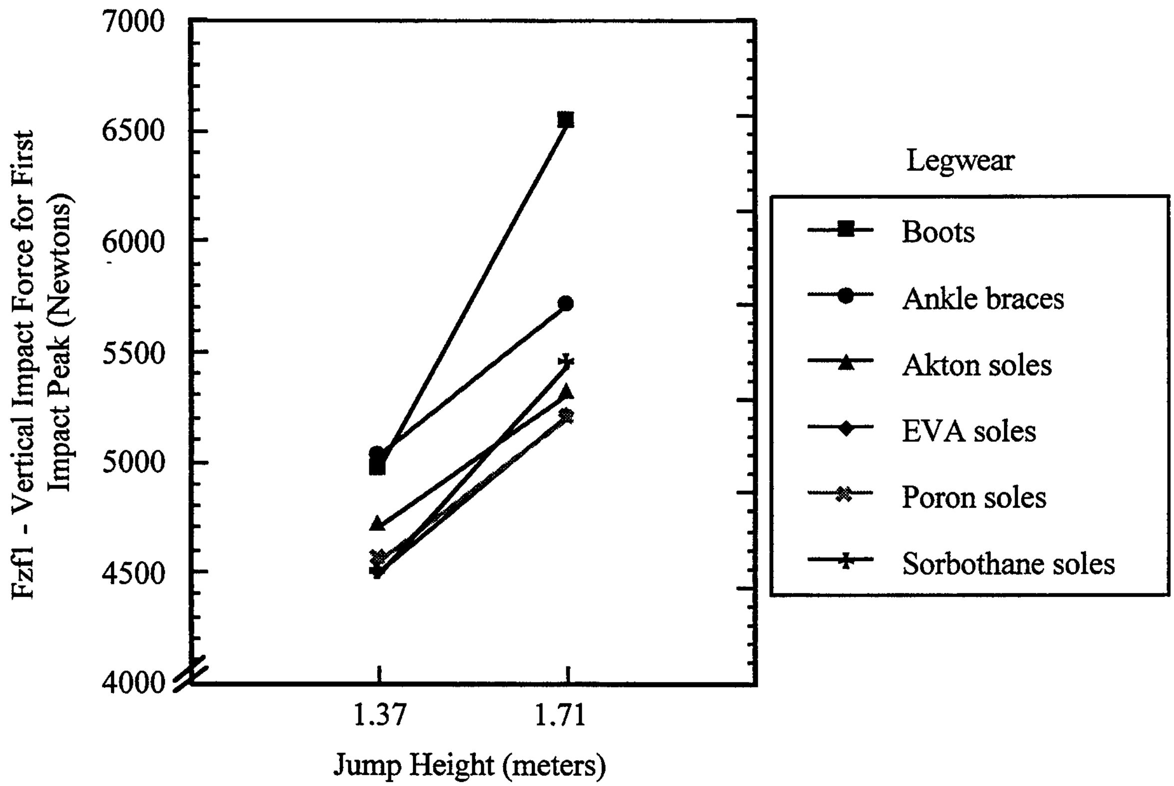

Figure 30. Experiment II: Vertical impact force during the first impact peak versus jump height by legwear.

Horizontal Force During Toe Touchdown (Frfl)

As indicated earlier, the horizontal resultant forces at F1 impact differed significantly across jump heights. These Frfl forces averaged 1744 N (2.2 times body weight) at 1.37 m and 2064 N (2.7 times body weight) at 1.71 m. ANOVA results shown in

Table 23 reveal no significant effects of legwear nor jump height-legwear interaction on Frf1 results.

Vertical Force at Heel Touchdown (Fzf2)

During the F2 impact event of heel contact, the interaction of jump height elevation and legwear conditions caused significant differences in the vertical impact forces (see Table 23). Examination of Figure 31 reveals that the absorption soles' F2 results were greatly influenced by a change in jump height. Among the soles, the EVA material produced the greatest Fzf2 results at 1.37 m and the lowest at 1.71 m. The difference in Fzf2 impact between the Sorbothane and Akton soles did not occur at the 1.71-m jump height. Fzf2 forces averaged 6982 N (8.9 times body weight) to 14536 N (18.6 times body weight). In addition, post hoc comparison indicated greater spread between boots and ankle braces' Fzf2 results and the soles' impact forces.

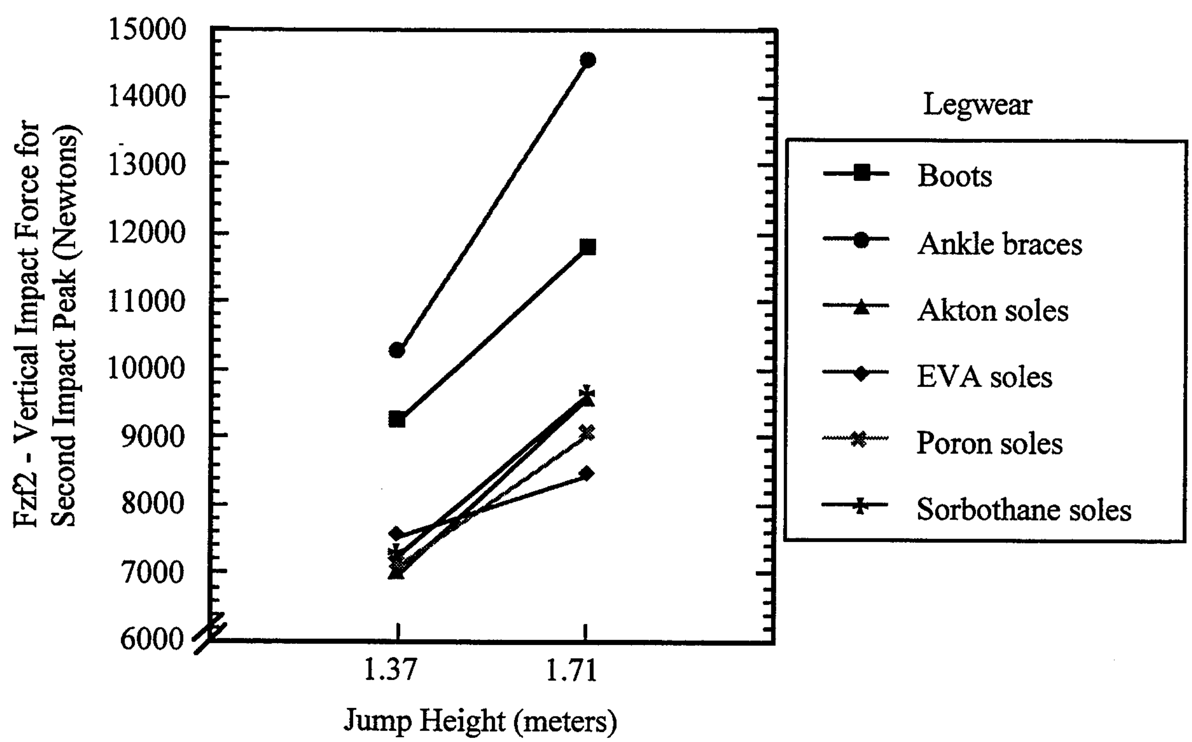

Figure 31. Experiment II: Vertical impact force during the second impact peak versus jump height by legwear.

As expected, the absorption soles afforded significant reductions in Fzf2 when compared to boots and ankle braces landings. This reduction ranged from 20% to 33%. With respect to the absorption soles, soldiers experienced the lowest Fzf2 forces with the

EVA soles and the highest with the Sorbothane soles. Biomechanically meaningful differences existed between the soles' Fzf2 impact results.

Horizontal Force at Heel Touchdown (Frf2)

According to Table 23, soldiers' horizontal impact at heel contact, Frf2, also varied significantly because of interactions between jump height and legwear conditions. Unlike Fzf2 results, jump height elevation caused minimal increases in the absorption soles Frf2 impact forces. Only the boots and ankle braces conditions had large increases in these horizontal forces as jump height increased. Surprisingly, wearing the EVA soles on the 1.37-m jumps produced Frf2 forces 1700 N greater than boots only impacts (see Figure 32).

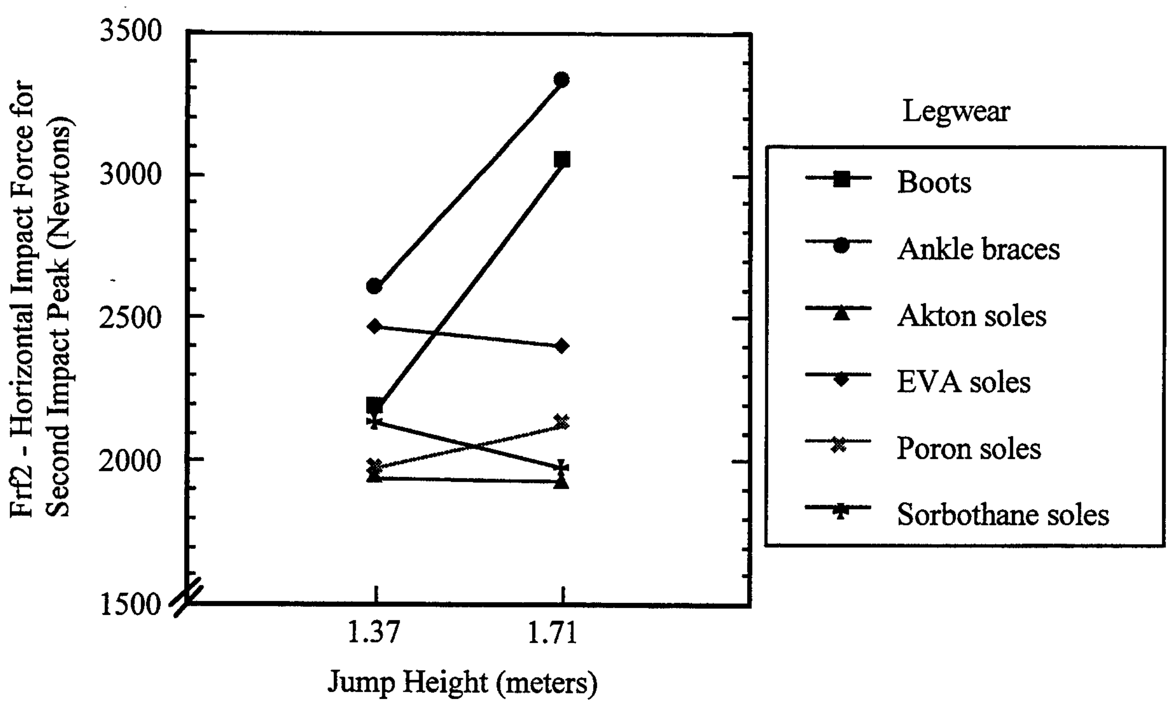

Figure 32. Experiment II: Horizontal impact force during the second impact peak versus jump height by legwear.

Similar to Fzf2 ANOVA results, legwear conditions produced highly significant differences in Frf2 results. Again, the boots and ankle braces conditions had the highest Frf2 forces, 2617 N and 2967 N, respectively. In comparision to these results, the Akton soles offered significant force reductions of 27% and 35%, respectively. The Poron and Sorbothane materials also had significantly lower FrF2 impact levels with respect to the ankle braces landings. Further examination of the soles' performances revealed 100-N differences between the Akton or EVA Frf2 results and the intermediate Frf2 levels for the Poron and Sorbothane materials.

Impact at the End of Reactive Absorption (Fzend, Frend)

With the end of the reactive landing phase, a paratrooper's landing motions become more proactive until PLF completion. This event is determined by the maximization of knee bend to finish initial impact absorption. The resulting vertical ground reaction force, Fzend, approximates the soldier's body weight. ANOVA results shown in Table 23 indicate significant differences in Fzend results for the legwear approaches. As expected, soldiers experienced the highest Fzend forces, 1300 N, while wearing boots or ankle braces. The absorption soles significantly reduced these forces by 200 N. No statistically significant nor biomechanically meaningful differences were detected between the absorption soles' performances.

Statistical analysis revealed no significant differences for the horizontal resultant forces, Frend, accompanying the end of reactive absorption. These Frend forces ranged from 355 N to 498 N.

Percent Force Change Between Legwear Approaches and Boots

As in Experiment I, we calculated the percent force changes offered by the ankle braces and absorption soles during maximum vertical and horizontal impact. These calculations afforded a direct evaluation of force reduction capabilities over the standard combat boot landings.

According to Table 24, the resulting percent force changes at maximum vertical impact, Pdfzmax, varied significantly for jump height and legwear combinations. It was expected that larger percent changes would occur with jump height elevation. As seen in Figure 33, this occurred with the ankle braces, EVA soles, and Poron soles. Surprisingly, the Akton and Sorbothane soles did not offer increased force reduction at the 1.71-m jump height. Figure 33 indicates the percent changes ranged from 27.1% (force increase) to -24.2% (force reduction).

ANOVA results shown in Table 24 reveal that the Pdfzmax results were also influenced by legwear worn. The ankle braces increased maximum vertical impact by 22.2%, while the soles reduced Fzmax 16.4% to 19.2%. The absorption sole approach was a significant improvement over the ankle braces. Scheffé testing indicated that no significant differences were detected among the percent force changes of the absorption soles. In comparision to Experiment I results, the soles offered greater Fzmax reduction than the viscoelastic material.

Table 24

Experiment II: ANOVA Results for Percent Changes of Maximum Vertical and Horizontal Resultant Forces

Variable	Effect	F-ratio	*p*-value
Pdfzmax	Jump height	F(1,22)= 0.14	ns
	Legwear	F(4,19)= 28.63	$p<.001$
	Jump height x legwear	F(4,19)= 7.31	$p<.01$
Pdfrmax	Jump height	F(1,20)= 9.48	$p<.01$
	Legwear	F(4,17)= 11.44	$p<.001$
	Jump height x legwear	F(4,17)= 0.20	ns

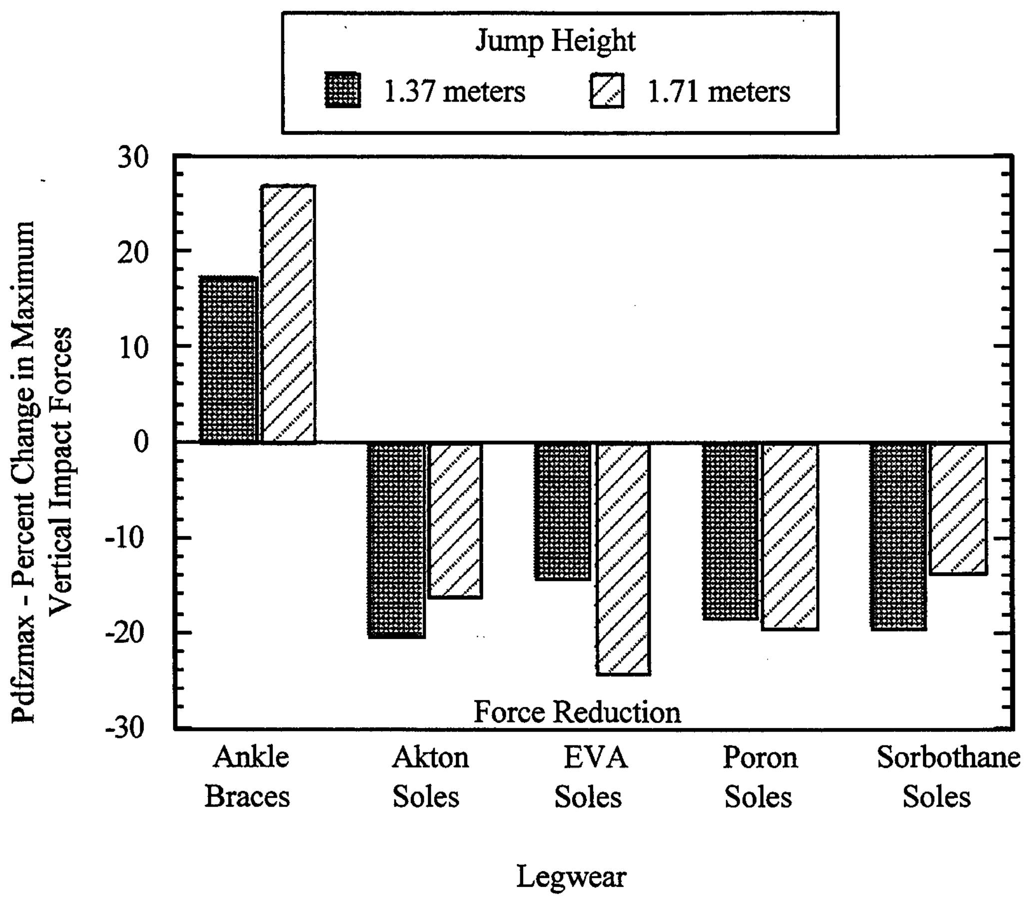

Figure 33. Experiment II: Percent changes in maximum vertical impact versus legwear by jump height.

The percent force changes at maximum horizontal impact, Pdfrmax, exhibited significant differences for jump height elevation and legwear approach (see Table 24). As expected, larger percent force changes occurred at the 1.71-m jump height. With respect to legwear approach, the absorption soles again offered a significant improvement in force absorption over the ankle braces. Similar to Pdfzmax results, the soles reduced Frmax impact forces 4.7% to 10.3%, while the ankle braces produced a force increase of 18.4%. Table 25 indicates that the Akton soles afforded the greatest Frmax reduction with respect to boots only landings. Post hoc comparisons between the soles' Pdfrmax results revealed no significant differences. The soles' percent force reduction of Frmax was smaller than the decrease afforded by the viscoelastic material landing surface used in Experiment I.

Table 25

Experiment II: Percent Changes in Impact Forces by Bracing and Force-Attenuating Legwear

Legwear	Percent change in maximum horizontal impact force
Ankle braces	18.4
Poron soles	-5.3
EVA soles	-4.7
Sorbothane soles	-5.9
Akton soles	-10.3

Note. Percent changes were calculated with respect to combat boot landing impact forces and averaged for descent velocities 5.18 and 5.79 m/s. Negative values indicate force reductions, and positive values denote force increases.

Moments

We again examined the torsional effects of the PLF by measuring the vertical moments of the reactive landing phase. In comparison to Experiment I results, these ground reaction moments were smaller. We believe reductions occurred as a result of the different landing orientation, right-side PLF, used in Experiment II along with an adjustment of the force plate system. Soldiers' PLF performances with a right-side landing appeared to be more fluid, with less hesitation and the planting of the feet following heel touchdown. Analyses of the moments' measurements made in Experiment II again affirmed the efficacy of the soles to reduce impact. However, we were not able to statistically delineate between the individual materials' performances. (See Table 26 for a listing of the statistical analyses results for the moment measurements.)

Table 26

Experiment II: ANOVA Results for Moments About the Vertical Axis

Variable	Effect	F-ratio	*p*-value
Mzmax	Jump height	F(1,17)= 62.09	*p*<.001
	Legwear	F(5,13)= 15.39	*p*<.001
	Jump height x legwear	F(5,13)= 1.80	ns
Mzfzmx	Jump height	F(1,16)= 3.19	ns
	Legwear	F(5,12)= 2.48	ns
	Jump height x legwear	F(5,12)= 0.47	ns
Mzfrmx	Jump height	F(1,16)= 9.55	*p*<.01
	Legwear	F(5,12)= 14.81	*p*<.001
	Jump height x legwear	F(5,12)= 0.52	ns
Mzf1	Jump height	F(1,15)= 1.04	ns
	Legwear	F(5,11)= 1.91	ns
	Jump height x legwear	F(5,11)= 1.93	ns
Mzf2	Jump height	F(1,14)= 2.18	ns
	Legwear	F(5,10)= 3.43	*p*<.05
	Jump height x legwear	F(5,10)= 1.53	ns
Mzend	Jump height	F(1,17)= 0.67	ns
	Legwear	F(5,13)= 5.09	*p*<.01
	Jump height x legwear	F(5,13)= 0.41	ns

Maximum Vertical Moment (Mzmax)

As indicated in Table 26, both jump height and legwear conditions significantly affected the maximum vertical moment, Mzmax, experienced by soldiers. Mzmax measurements increased nearly 50% as jump height rose from 1.37 m to 1.71 m: 949 Nm versus 1388 Nm. Landing with the absorption soles afforded significant moment reduction over the boots-only or ankle braces' conditions. EVA soles produced the smallest Mzmax average. Figure 34 indicates the Mzmax averages by legwear condition.

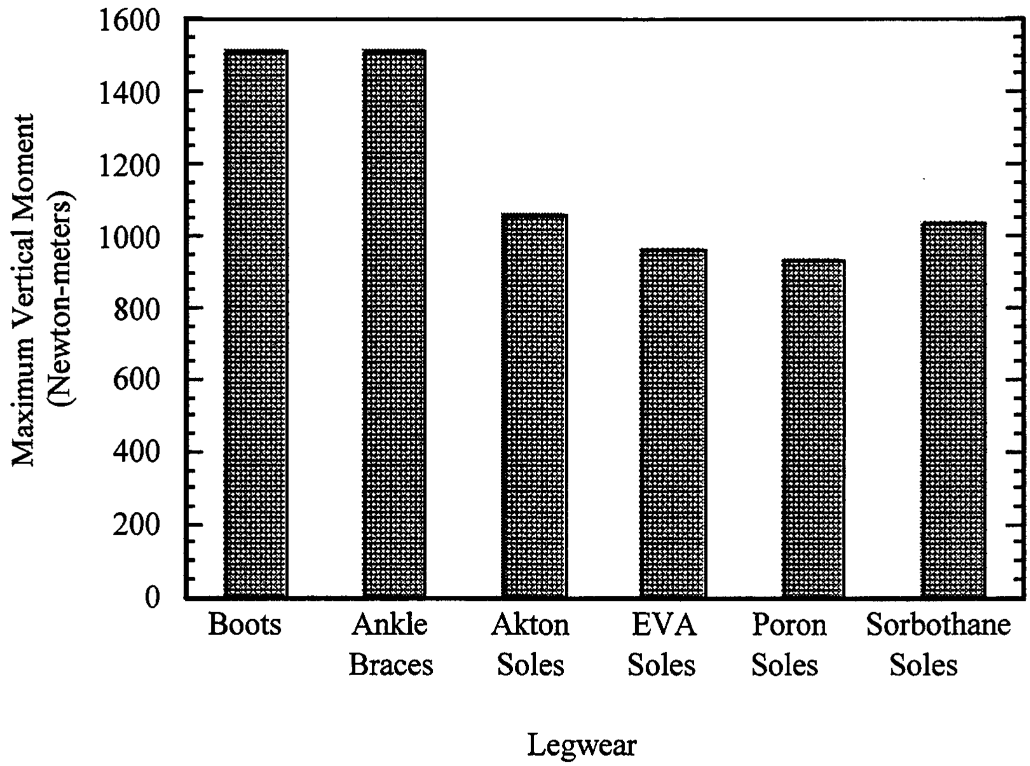

Figure 34. Experiment II: Maximum moment about the vertical axis by legwear.

Vertical Moments at Toe Touchdown and Maximum Vertical Impact (Mzfl and Mzfzmax)

According to ANOVA results in Table 26, the ground reaction moments during toe touchdown (Mzfl) and maximum vertical impact (Mzfzmax) were not significantly affected by the experiment's jump height nor legwear conditions. Toe touchdown resulted in torsional forces about the feet, which ranged from 180 Nm to 430 Nm. Wearing the absorption soles reduced these torsional forces as opposed to boots-only landings. The Poron soles averaged the lowest Mzfl reading.

During maximum vertical impact, ground reaction moments averaged 282 Nm to 890 Nm. Again, soldiers experienced the greatest Mzfzmax readings when wearing combat boots alone. Statistical testing revealed that landings in the EVA or Poron soles allowed a marginal reduction in moments ($p<.10$) in comparison to boots-only landings.

Vertical Moment at Maximum Horizontal Impact (Mzfrmax)

The compressive nature of the absorption soles significantly lowered the ground reaction moment during maximum horizontal impact. As shown in Table 27, the soles' Mzfrmax averages were 266 Nm to 489 Nm below the boots' and ankle braces' averages. This reduction by the EVA soles was nearly 50%. Besides legwear, jump height influenced the Mzfrmax results (see Table 26).

Table 27

Experiment II: Moments About the Vertical Axis

Legwear	Mzfrmax	Vertical moments (Nm) Mzf2	Mzend
Boots	728.37	897.67	146.98
Boots + ankle braces	801.33	646.72	216.07
Akton soles	445.50	494.86	157.29
EVA soles	311.96	298.25	171.36
Poron soles	382.64	375.18	137.86
Sorbothane soles	461.89	439.99	153.29

Vertical Moment at Heel Touchdown (Mzf2)

Statistical analysis for the vertical moments at heel touchdown revealed similar legwear effects as mentioned for Mzfrmax. These statistical results for Mzf2 are summarized in Table 26. Table 27 indicates landings in boots produced the highest Mzf2 moment average, 898 Nm, while the EVA soles averaged only 298 Nm. Surprisingly, jump height did not produce statistically significant differences in Mzf2.

Vertical Moment at the End of Reactive Absorption (Mzend)

At the end of the reactive landing phase, soldiers experienced ground reaction moments ranging from 138 Nm to 216 Nm. When compared to Mzend measures for boots-only landings, only the Poron soles offered a reduction of the ground reaction moments. Post hoc testing revealed that the Poron soles had a significantly lower Mzend average than the ankle braces' landings. Table 27 summarizes these Mzend moment measurements. The Poron material may have allowed greater compression or stability to reduce twisting about the feet. Table 26 indicates that jump height had no significant effect on Mzend measurements.

Impulses

In Experiment I, landings on the viscoelastic material allowed large vertical force impulses. We wanted to examine whether the absorption soles, containing the same thickness of damping material, could offer similar force absorption. Table 28 summarizes the ANOVA results for the impulse variables.

Table 28

Experiment II: ANOVA Results for Vertical Force Impulses

Variable	Effect	F-ratio	*p*-value
Impf1	Jump height	F(1,20)= 2.89	ns
	Legwear	F(5,16)= 14.68	p<.001
	Jump height x legwear	F(5,16)= 0.35	ns
Impf2	Jump height	F(1,20)= 4.25	ns
	Legwear	F(5,16)= 8.70	p<.001
	Jump height x legwear	F(5,16)= 1.53	ns
Impf12	Jump height	F(1,20)= 2.68	ns
	Legwear	F(5,16)= 4.43	p<.05
	Jump height x legwear	F(5,16)= 1.75	ns
Impf2end	Jump height	F(1,20)= 1.37	ns
	Legwear	F(5,16)= 9.23	p<.001
	Jump height x legwear	F(5,16)= 1.71	ns

The ANOVA results in Table 28 revealed that jump height variation did not affect the impulse measurements during the reactive landing phase. However, significant impulse differences did exist between the legwear conditions. When compared to the boots-only and ankle braces' conditions, soldiers' PLFs with the absorption soles generally produced higher impulse measurements.

Vertical Impulse to Toe Touchdown (Impf1)

Between initial contact and toe touchdown, soldiers' PLFs produced impulses averaging 26.17 Ns to 36.49 Ns. Statistical evaluation of the Impf1 legwear averages in Table 29 indicated that the Akton, Poron, and Sorbothane soles significantly improved vertical force absorption compared to the boots and ankle braces. The soles' material properties afforded increased absorption times resulting in the higher impulse measurements. Table 29 lists the Impf1 averages measured for the six legwear conditions.

Table 29

Experiment II: Vertical Force Impulses During Impact Events

Legwear	Vertical force impulses (Ns) Impf1	Impf2	Impf2end
Boots	30.32	133.41	212.58
Boots + ankle braces	26.17	129.37	215.57
Akton soles	36.27	149.60	232.86
EVA soles	34.93	161.09	215.30
Poron soles	36.97	152.58	228.39
Sorbothane soles	36.49	149.94	236.13

Vertical Impulse between Toe and Heel Touchdown (Impf12)

Wearing the EVA soles afforded paratroopers superior force absorption between toe and heel touchdown. The Impf12 measurement for the EVA soles, 34.93 Ns, was significantly greater than the boots and ankle braces averages of 30.32 Ns and 26.17 Ns, respectively. The EVA material offered a large absorption time coupled with low F1 and F2 vertical forces. The Akton, Poron, and Sorbothane soles also benefited force absorption between the F1 and F2 impacts; however, this improvement was not significant with respect to the other legwear conditions.

Vertical Impulse to Heel Touchdown (Impf2)

For the PLF period encompassing contact to heel touchdown, post hoc testing revealed that landing with absorption soles significantly increased vertical impulses with respect to boots' and ankle braces' conditions (see Table 28). According to Table 29, the

EVA soles again had the largest Impf2 result, 161.09 Ns, whereas the Akton, Poron, and Sorbothane soles averaged 150 Ns. The soles' force absorption performance was favorable to PLF impact attenuation as it included smaller impact forces spread over somewhat longer time intervals.

Vertical Impulse Between Heel Touchdown and the End of Reactive Absorption (Impf2end)

When soldiers progressed through the last period of the reactive landing phase, they experienced large impulses while wearing the Sorbothane, Akton, or Poron soles. During the PLF F2-end segment, Sorbothane and Akton afforded favorable force absorption by lengthening the time interval and lowering impact force. These improvements were significant when compared to landing results for the boots-only and ankle braces' conditions. Surprisingly, EVA soles did not produce favorable impact absorption during the F2-end segment. Tukey testing indicated that the EVA soles' Impf2end average was significantly less than the Sorbothane soles' average. (See Table 29 for a listing of the Impf2end values.)

Absorption Times

Absorption times were again calculated for the impact periods during the PLF reactive landing phase. It was hoped that these times would provide further delineation between the performances of the attenuation materials used in the sole prototypes. We believe that this delineation is most important for the contact-F1, F1-F2, and contact-F2 periods in which the greatest impact forces are experienced. The ANOVA results for these time measurements are listed in Table 30.

Time to Toe Touchdown (F1time)

The time interval between contact and the first impact peak, F1time, ranged between 13.1 msec and 16.7 msec. As expected, these time measurements were significantly affected by jump height: F1 peak absorption times averaged 16.3 msec for 1.37-m jumps and 14.8 msec for 1.71-m jumps. Table 30 indicates that soldiers' F1 impact times also differed significantly across the legwear conditions. All soles allowed greater absorption time than the boots-only and ankle braces conditions. These time differences were statistically significant for all Scheffé tests between the soles and the ankle braces' F1time averages. Akton, Poron, and Sorbothane soles each afforded 2+ msec more absorption time than did the boots only (see Table 31). Post hoc testing indicated no differences among soles' time averages.

Table 30

Experiment II: ANOVA Results for Impact Times

Variable	Effect	F-ratio	*p*-value
Frmaxtime	Jump height	F(1,20)= 10.88	*p*<.01
	Legwear	F(5,16)= 11.12	*p*<.001
	Jump height x legwear	F(5,16)= 0.90	ns
F1time	Jump height	F(1,20)= 30.89	*p*<.001
	Legwear	F(5,16)= 10.45	*p*<.001
	Jump height x legwear	F(5,16)= 0.60	ns
F2time	Jump height	F(1,20)= 83.28	*p*<.001
	Legwear	F(5,16)= 12.93	*p*<.001
	Jump height x legwear	F(5,16)= 0.75	ns
F12time	Jump height	F(1,20)= 65.72	*p*<.001
	Legwear	F(5,16)= 11.45	*p*<.001
	Jump height x legwear	F(5,16)= 1.84	ns
F2endtime	Jump height	F(1,20)= 21.51	*p*<.001
	Legwear	F(5,16)= 4.55	*p*<.01
	Jump height x legwear	F(5,16)= 1.65	ns
Totaltime	Jump height	F(1,20)= 52.86	*p*<.001
	Legwear	F(5,16)= 11.81	*p*<.001
	Jump height x legwear	F(5,16)= 1.04	ns

Table 31

Experiment II: Time Intervals During the Reactive Landing Phase

	Time intervals (msec)			
Legwear	F1time	F2time	F12time	Totaltime
Boots	14.3	37.6	23.3	109.5
Boots + ankle braces	13.1	32.4	19.4	96.5
Akton soles	16.6	37.2	20.6	108.2
EVA soles	15.9	38.7	22.8	105.0
Poron soles	16.7	38.2	21.5	109.4
Sorbothane soles	16.7	37.9	21.1	110.5

Time to Maximum Horizontal Impact (Frmaxtime)

Unlike the results in Experiment I, soldiers experienced the maximum horizontal resultant force after the second peak, not between the two impact peaks. We believe that the timing difference occurred because soldiers performed a right-front PLF in Experiment I and a right-side PLF in Experiment II. The right-front PLF may have been conducive to better PLF control during the reactive landing phase, so soldiers did not use a twisting motion to stabilize their feet following toe touchdown. As with the first experiment, increasing jump height did significantly reduce the time to maximum horizontal impact. Jump height elevation from 1.37 m to 1.71 m decreased Frmaxtime by 3.8 msec. When soldiers wore the prototype soles, their Frmaxtimes averaged approximately 44 msec. Table 30 reveals that this absorption time was an improvement over the boots-only averages of 41.1 msec, and a significant increase over the Frmaxtimes for ankle braces landings.

Time to Heel Touchdown (F2time)

As indicated in Table 30, both jump height and legwear significantly affected the time period to soldier's heel touchdown, F2time. Their impact times averaged 32.4 msec to 38.7 msec. The prototype soles of EVA, Poron, and Sorbothane materials afforded the paratrooper slightly longer F2times than when only boots were worn. However, Scheffé testing revealed that all the soles' and the boots-only conditions produced significantly larger F2 intervals with respect to the ankle braces' landings. Table 31 summarizes the F2time averages for the different legwear approaches.

Time Between Toe and Heel Touchdown (F12time)

The ANOVA indicated significant effects for jump height and legwear conditions upon the time interval between the F1 and F2 impact peaks (see Table 30). Because of increased descent velocities, jump height elevation decreased the time period from toe to heel touchdown. Surprisingly, when soldiers performed PLFs in the boots-only condition, these landings produced the longest F12time averages. The absorption soles' smaller F12times indicate that the time to second impact for the soles' landings was driven by the contact-F1 interval. As shown in Table 31, the EVA material afforded the longest F12times among the attenuation soles. Scheffé testing identified that the EVA soles' and the boots-only conditions produced significantly greater peak-to-peak absorption times than the ankle braces' legwear did.

Time Between Heel Touchdown and End of Reactive Absorption (F2endtime)

During the last period of the reactive landing phase, there was a significant reduction of absorption time between the 1.37-m and 1.71-m jumps, 74.3 msec versus 66.2 msec, respectively (see Table 30). PLFs made in the Akton, Poron, or Sorbothane soles were afforded longer F2endtimes than in the boots only legwear condition. However, these time improvements were not significant. As usual, the ankle braces had the shortest absorption times, which were significantly worse in comparison to the Sorbothane soles. Surprisingly, wearing the EVA soles did not benefit the paratroopers in the F2-end period.

Total Reactive Absorptive Time (totaltime)

The time length of the reactive landing phase ranged from 96.5 msec to 110.5 msec. As expected, the totaltime averages differed significantly for the two jump heights of 1.71 m and 1.37 m, 113.1 msec versus 99.8 msec, respectively. Comparison of the legwear time averages in Table 31 indicated that only the Sorbothane soles lengthened the reactive landing phase over the combat boots landings. However, post hoc testing revealed that all the absorption soles did provide significantly longer reactive landing periods than wearing just ankle braces and boots together.

Joint Angles

As in Experiment I, we evaluated the angular motion about the ankle and knee joints via "bend" or change in angle calculations. Through this examination, we could determine if the soles promoted greater joint bending while reducing PLF impact forces and moments. The statistical analysis results for joint "bends" are detailed in Table 32.

Statistical evaluation of the ankle and knee "bends" for the various PLF intervals revealed no significant influence of jump height conditions, merely the trend of decreased joint bending with increased jump height. This lack of jump height effect on joint bending is probably attributable to the consistent and similar performance of the absorption soles.

Ankle Bend

Between initial contact and toe touchdown, paratroopers bent their ankles 15.3° to 22.3°. Examination of the AAcontact and AAf1 angles in Figure 35 indicates that the absorption soles did not promote greater ankle bend. In fact, soldiers' landings in the EVA soles and ankle braces conditions resulted in significantly lower Caafl measurements, thus producing the statistical results in Table 32.

Table 32

Experiment II: ANOVA Results for Changes in Ankle and Knee Angles

Variable	Effect	F-ratio	*p*-value
Caafl	Jump height	F(1,17)= 0.19	ns
	Legwear	F(5,13)= 5.93	*p*<.01
	Jump height x legwear	F(5,13)= 1.98	ns
Caaf2	Jump height	F(1,17)= 1.92	ns
	Legwear	F(5,13)= 12.04	*p*<.001
	Jump height x legwear	F(5,13)= 1.10	ns
Caafl2	Jump height	F(1,17)= 1.86	ns
	Legwear	F(5,13)= 2.77	ns
	Jump height x legwear	F(5,13)= 1.54	ns
Ckafl	Jump height	F(1,17)= 0.48	ns
	Legwear	F(5,13)= 1.57	ns
	Jump height x legwear	F(5,13)= 1.67	ns
Ckaf2	Jump height	F(1,17)= 0.37	ns
	Legwear	F(5,13)= 3.56	*p*<.05
	Jump height x legwear	F(5,13)= 1.28	ns
Ckafl2	Jump height	F(1,17)= 0.05	ns
	Legwear	F(5,13)= 3.37	*p*<.05
	Jump height x legwear	F(5,13)= 0.87	ns

As soldiers progressed from toe to heel touchdown, their ankles bent an additional 20.3° to 25.4°. However, Table 32 indicates that no significant differences were present between these legwear averages for Caafl2.

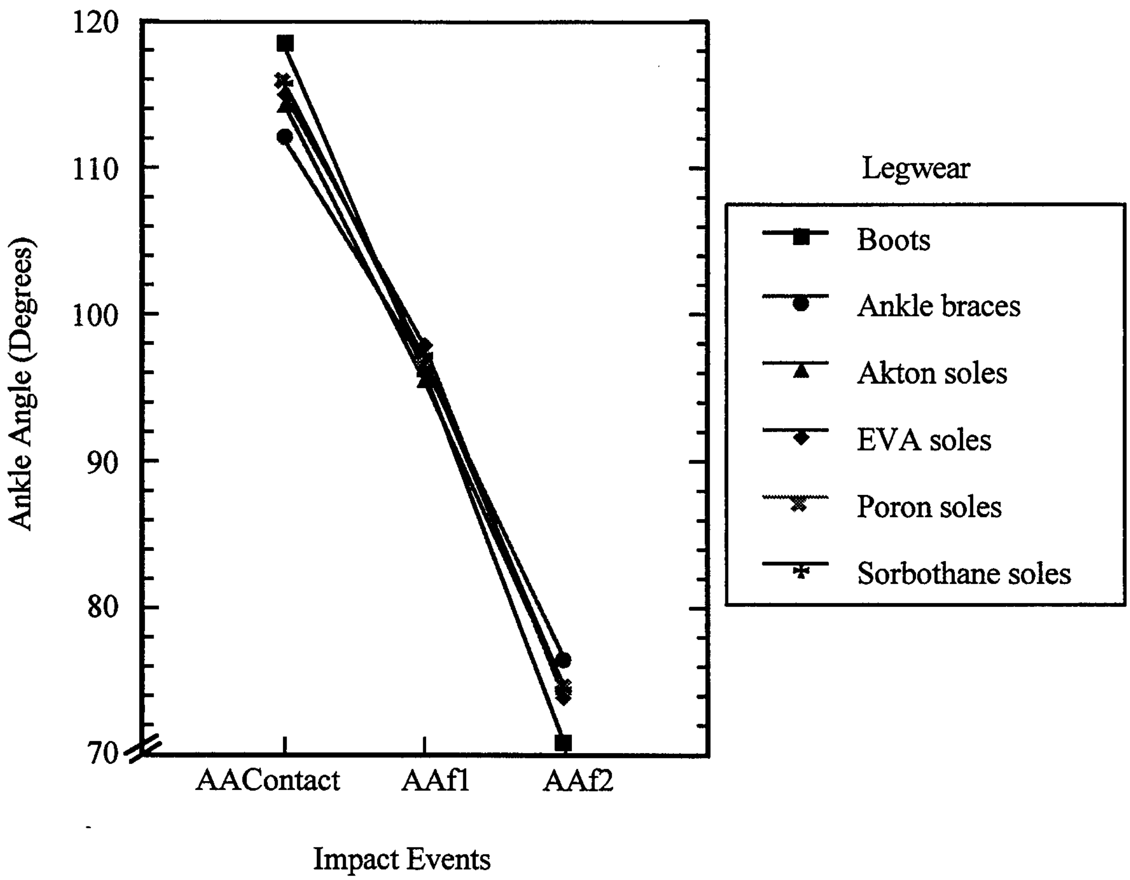

Figure 35. Experiment II: Ankle angles versus impact events by legwear.

During the contact-F2 impact interval of the reactive landing phase, neither the absorption soles nor the ankle braces legwear conditions produced more ankle bend than wearing boots only. The EVA, Poron, and Sorbothane soles produced the same amount of ankle bend. This is evident in Figure 35 where the ankle bend between contact and F2 impact, Caaf2, averaged 35.6° to 47.7°. We have two theories why these significant performance decrements occurred: the ankle braces' rigidity may limit ankle flexion; and the inflexibility of the absorption soles at the soldier's ball of the foot may foster a more flat-footed landing.

Knee Bend

In Experiment II, the average measurement of soldiers' knee angles changed from 168.6° at initial contact to 159.5° at heel impact. During the contact-F1 impact segment of the reactive landing phase, soldiers only bent their knees an additional 8° to 10°. As indicated in Table 32, these small changes, Ckafl, were not significantly affected by the paratroopers' legwear. However, as soldiers' PLFs progressed through heel touchdown, more marked differences were seen for the measurements Ckafl2 and Ckaf2 (see Table 32).

During the contact-F2 and F1-F2 PLF segments, soldiers attained the largest knee bend while wearing the absorption soles. Between the F1 and F2 impact peaks, EVA produced the most knee bend, 23.1°. This result was a significant improvement in comparison to the 19.5° value for ankle braces landings. Similarly, EVA, along with the Poron and Sorbothane soles, significantly increased knee bend for the contact-F2 segment. During this period between PLF contact and the F2 impact, knee bend ranged from 27.4° to 32.3°. These knee angle changes between the impact events of contact, F1 impact, and F2 impact can be seen in Figure 36.

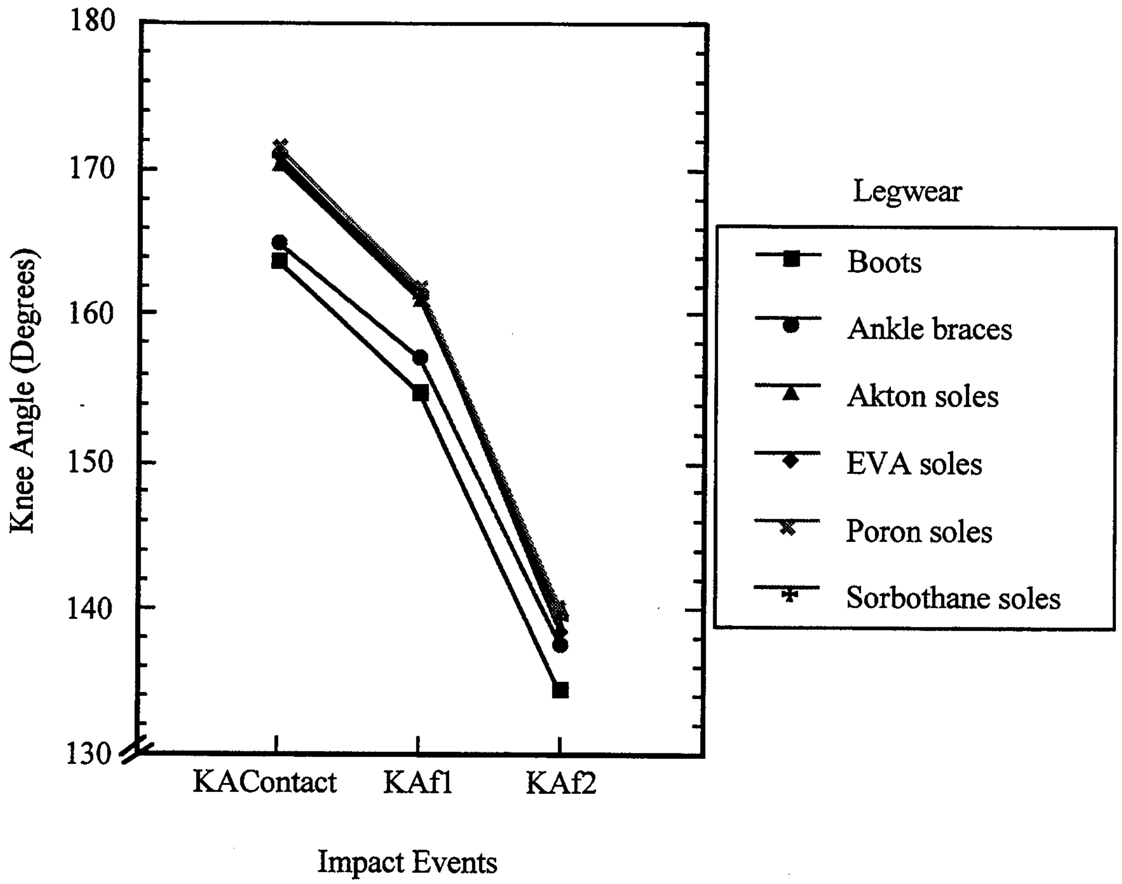

Figure 36. Experiment II: Knee angles versus impact events by legwear.

Therefore, we conclude that the absorption soles' ability to increase knee bend may have facilitated their superior reduction of PLF impact forces and moments.

Subjective Measures

In Experiment II, the paratroopers again completed post-jump and post-study questionnaires. We used these surveys to examine whether the soldiers perceived the prototype attenuation soles as beneficial for impact reduction. In addition, soldiers reviewed design options and noted the necessity for incorporation into impact-attenuation equipment. Twenty-four soldiers provided feedback about the PLF surveys. Their jump experience averaged 24 PLFs since completion of airborne training.

On the post-jump questionnaires, soldiers rated each of their PLF performances for overall contact (Rlandopn), walking and pre-jump posture mobility (Mobopn), initial landing contact (Ilandopn), and rolling and twisting feasibility (Rollopn). We used hierarchical loglinear analyses to examine if the jump height and legwear conditions affected soldiers' opinions about their landings.

Overall contact ratings (Rlandopn) were made on a continuous scale with one-unit gradations ranging from 0 to 10. Three descriptors anchored this scale: 0 indicated "softest landing," 5 denoted "average or boot-like landing," and 10 indicated "hardest landing." Soldiers did not record a Rlandopn rating for the boots only legwear condition. This condition served as a baseline to which the other landings were compared. To facilitate the hierarchical loglinear analysis, we compressed the Rlandopn responses into three categories: "softer," "average," and "harder."

Soldiers rated all six legwear conditions with respect to the Mobopn, Ilandopn, and Rollopn variables. Using past jump experience, soldiers rated these performance indicators as "easier," "more difficult," and "no different than usual."

Soldiers' ratings of the four performance variables were tabulated into cells with respect to opinion response, jump height, and legwear categories. Since all cells did not have responses, a Δ of 1.0 was added to each cell frequency before hierarchical loglinear analysis.

Hierarchical loglinear results indicated that responses for the four subjective variables could not be modeled as a three-way interaction among opinion, jump height, and legwear. As a result, we could determine the responses to the Rlandopn, Mobopn, and Ilandopn measures with a model involving the main effects of opinion and legwear along with their interaction. Only the main effect of opinion level statistically modeled the responses for the Rollopn measure (see Table 33).

Table 33

Experiment II: Significant Hierarchical Loglinear Results for Post-Jump Questionnaire Landing Ratings

Variable	Sample size	Effect	df	Partial chi-square value	*p*-value
Rlandopn	n=24	Opinion	2	106.42	$p<.001$
		Legwear*Opinion	8	27.87	$p<.01$
Mobopn	n=24	Opinion	2	129.56	$p<.001$
		Legwear*Opinion	10	47.40	$p<.001$
Ilandopn	n=24	Opinion	2	58.86	$p<.001$
		Legwear*Opinion	10	108.52	$p<.001$
Rollopn	n=24	Opinion	2	96.97	$p<.001$

As indicated in Table 33, legwear conditions significantly interacted with opinion ratings on overall landing performance (Rlandopn), mobility (Mobopn), and initial landing contact (Ilandopn). For overall landing performance, soldiers were more likely to categorize ankle braces landings as "softer." In addition, soldiers felt the absorption soles produced predominantly "softer" or "boot-like" landings. The Sorbothane soles' ratings were significantly aggregated in the "softer" category.

The initial landing (Ilandopn) and mobility (Mobopn) measures provided some delineation between the legwear performances. With respect to the mobility measure, soldiers perceived mobility as significantly "more difficult" in the EVA, Poron, and Sorbothane soles. Akton sole Mobopn responses were not skewed toward any particular descripter. As expected, soldiers usually perceived their combat boot landings as "no different" from previous landing experiences. Paralleling the higher moment and force results, soldiers were less likely to give an "easier" rating for initial landing contact in boots or ankle braces. Conversely, a significant number of initial contact ratings for the Akton soles fell in the "easier" category. Soldiers' ratings of the other absorption soles did not significantly deviate from the expected response distribution

Table 33 hierarchical loglinear results indicate that soldiers' opinions for the four subjective perforomances were not evenly distributed in the three response categories. Generally, soldiers did not rate their overall PLF contacts (Rlandopn) "harder" than usual landings but believed them to reflect "average" landing performance. With respect to initial landing contact, soldiers' Ilandopn responses were significantly skewed from "more difficult" contact characterization to "easier." The favorable PLF contact afforded by the absorption soles drove these response patterns for the Rlandopn and Ilandopn measures. In contrast, the soles did not afford improved mobility during PLF performance, so Mobopn responses shifted from the "easier" to "more difficult" category. Finally, soldiers did not perceive any legwear to affect their ability to roll at the end of the PLF and generally rated this performance as "no different than usual."

On the post-study questionnaire, soldiers reviewed their PLF performances and ranked the legwear conditions for wear comfort and overall performance. The numerical rankings were mutually exclusive for these two subjective measures. A lower numerical ranking indicated better performance. We evaluated these measures using two chi-square tests, the Friedman Test and Kendall's Coefficient of Concordance Test.

Paratroopers rated wear comfort of the three legwear approaches: combat boots, ankle braces, and absorption soles. Friedman testing revealed no significant differences between the wear comfort rankings. The overall performance rankings of the six legwear conditions exhibited significant differences [$X^2(5, \underline{N}=22)=16.62, p<.01$] yet lower rater concordance [W=0.15]. Soldiers' order of preference (from best to worst) was boots only, Sorbothane soles, Poron soles, Akton soles, ankle braces, and EVA soles. We believe the soles did not receive the top ranking because of novelty and mobility factors, rather than PLF performance decrement.

Soldiers again provided feedback about possible design criteria for prototype equipment development. The ten top-rated characteristics are displayed in Figure 37. As in Experiment I, soldiers selected easy to don, adjustable fit, portable and lightweight, and foot cushioning as the most important features.

Conclusions and Recommendations

Impact-Absorbing Soles Versus Boots and Ankle Braces

The hypothesis of this experiment was there will be no difference in the results for jumps from the same height as a function of the cushioning material attached to the test participant's boots. Based on the results of the experiment, the hypothesis is accepted when the impact-absorbing soles are compared to one another, and the hypothesis is rejected when the results of the jumps with the impact-absorbing soles are compared to the results for jumps in boots only or jumps with ankle braces. There are a few exceptions to the previous statement.

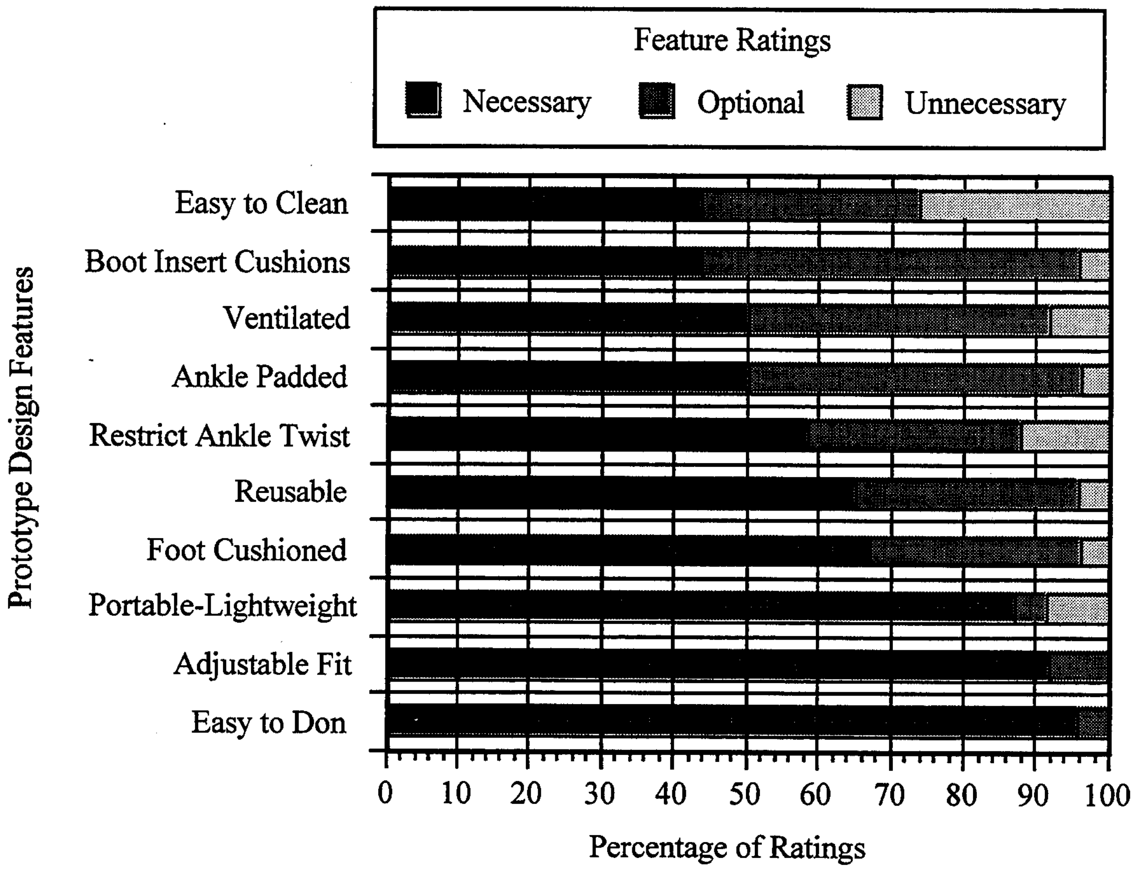

Figure 37. Experiment II: Ratings for the ten most preferred prototype design features.

Six variables measured showed no statistical differences as a function of legwear. Those variables are Frfl, Frend, Mzfzmx, Mzfl, Caafl2, and Ckafl. Three of these variables are the same ones that showed no statistical difference as a function of legwear in Experiment I. These variables are not statistically different as a function of legwear for two main reasons. First, the PLF technique is such that legwear has no effect on certain variables. For example, because most of the bending occurs at the ankle during the time from contact to F1, there is very little bending at the knee from contact to F1, regardless of legwear. Second, the legwear conditions examined in this experiment are not very different from one another. Five of the six legwear conditions include the ankle brace, and four of the six legwear conditions are ankle braces and impact-absorbing soles.

Benefits of Impact-Absorbing Soles

The most important results of this experiment are the significant decreases in impact forces and moments recorded for jumps with the impact-absorbing soles when compared to jumps in boots only or jumps with the ankle brace. These decreases occur because the impact-absorbing soles act like the viscoelastic material used in Experiment I. The impact-absorbing soles and the viscoelastic material used in Experiment I both increase the time over which the impact is absorbed.

With the impact-absorbing soles, a jump from 1.71 m (5.6 ft) feels like a boots-only jump from 1.37 m (4.5 ft) or lower. In other words, a landing with the impact-absorbing soles at a descent rate of 5.79 m/s (19 ft/s) feels like a landing from a boots only jump at a lower descent rate such as 5.18 m/s (17 ft/s) or less. This reduction in impact forces is even better than the reduction achieved in Experiment I with the viscoelastic material. Wearing impact-absorbing soles should result in fewer injuries because injury rate is a function of descent rate (Pirson & Verbiest, 1985), and the impact-absorbing soles make the apparent descent rate lower.

The values for peak vertical and horizontal forces are not significantly different among the impact-absorbing soles, although, at the higher height, EVA soles have the lowest maximum vertical force and Akton soles have the lowest maximum horizontal force. This is a result of the response of the materials to the forces in these directions.

Pearson Correlation Coefficients

As expected, the Pearson correlation coefficients show that there are significant relationships between a paratrooper's weight and the forces, moments, impulses, impact times, and joint bending measured. The values measured for these variables increase as weight increases. The results of this experiment show that there are more significant relationships between leg length and the biomechanical variables measured than there are between stature and the biomechanical variables measured. This is different than the results from Experiment I. In Experiment I, there were more significant relationships between stature and the biomechanical variables than between leg length and the biomechanical variables. This may be because of the different legwear used in each experiment and because of different landings performed in each experiment. To resolve these issues, further investigation is required.

Further Development of a Device to Prevent PLF Injuries

The results of this experiment show that a device that incorporates the jump brace and impact-absorbing soles can significantly improve PLF performance compared to jumps in boots only or jumps with only the ankle brace. This type of device should be able to reduce injuries because it combines an ankle brace for stability and impact-absorbing sole for force and moment reduction.

Development of a prototype injury-prevention device for paratroopers should include ankle protection and impact-absorbing soles for force and moment reduction. The device's ankle support should allow more extension of the ankle than the jump brace permits. The soles need to be optimized for thickness, weight, impact-absorbing properties, and ease of movement during activities such as walking and running. The design of such a device must include the top four deign features identified in both experiments. It must be easy to don and doff, adjustable, portable and lightweight, and foot cushioning. The ideal impact-absorbing sole and ankle brace unit would protect the ankle from injuries attributable to twisting, allow normal extension of the ankle joint, be less than 3.81 cm (1.5 in.) thick, weigh less than 1.14 kg (2.51 lb) per pair, reduce vertical impact forces by 20% or more, reduce horizontal impact forces by 10% or more, and allow soldiers to walk and run short distances (less than 1 km [0.6 mi]) without significantly changing their gait.

For future development, knee protection should be examined. Perhaps something like the jump brace, which acts like a splint but allows the ankle to flex and extend, could be developed for the knee. This could be incorporated into a device like the one previously mentioned which cushions the foot and supports the ankle. Then hip protection could be included to complete the development of a lower extremity protective device.

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APPENDIX A

DATA COLLECTION FORM FOR ANTHROPOMETRIC MEASUREMENTS

DATA COLLECTION FORM FOR ANTHROPOMETRIC MEASUREMENTS

LEAP TEST PARTICIPANT DATA SHEET

NAME: ______________________________ **UNIT:** ____________________

SUBJECT IDENTIFICATION: Number [|]

DATE: Day [|] Month [|] Year [|]

BIRTH DATE: [|] [|] [|]

SERVICE ENTRY DATE: [|] [|]

RANK:_______ **HANDEDNESS:** R____ L____ Amb____

MOS:________ **SEX:**_____

Since completing airborne training, how many parachute jumps have you made? _______

ANTHROPOMETRIC MEASUREMENTS

1. **Weight** (lb) __________
1. **Weight** (kg)
2. **Stature**
3. **Cervicale Height**

4. **Trochanteric Height**
5. **Lateral Femoral Epicondyle Height**
6. **Lateral Malleolus Height**

7. **Trochanter to Back Wall**
8. **Lateral Femoral Epicondyle to Back Wall**
9. **Lateral Malleolus to Back Wall**

10. **Lateral Femoral Epicondyle to Side Wall**
11. **Lateral Malleolus to Side Wall**

12. **Foot Length**
13. **Foot Breadth**
14. **Ball of Foot Length**
15. **Heel-Lateral Malleolus Length**

16. **Bicondylar Breadth**
17. **Bimalleolar Breadth**

Footwear Correction Measurements

18. **Lateral Femoral Epicondyle Height** (Shod)
19. **Boot Sole Thickness**
20. **Sock Thickness** (Double)
21. **Heel Rear Wall Thickness**

*All measurements in millimeters except where noted.

APPENDIX B

DATA COLLECTION FORM FOR MARKER MEASUREMENTS

DATA COLLECTION FORM FOR MARKER MEASUREMENTS

LEAP TEST PARTICIPANT DATA SHEET

NAME: ______________________________ **UNIT:** ____________________

	Number		Jump Height		Legwear
SUBJECT IDENTIFICATION:					

	Day		Month		Year	
DATE:						

Transformation Measurements for Marker Locations (mm)

Marker Name	Distance to Side Wall	Distance to Back Wall	Distance to Floor
THIGH			
T1 (upper)			
T2 (middle)			
T3 (lower)			
SHANK			
S1 (upper)			
S2 (middle)			
S3 (lower)			
FOOT			
F1 (upper)			
F2 (heel)			
F3 (toe)			

APPENDIX C

EXPERIMENT I POST-JUMP QUESTIONNAIRE

EXPERIMENT I POST-JUMP QUESTIONNAIRE

Post-Jump Questionnaire

Subject Number:___________ Jump Height:_________ Date:_________

All test participants please answer the following questions about the PLF landing you just completed:

Compared to the parachute landings I have had, my landing in this study was______ (Select one answer.)

_______ softer than my softest landing.
_______ softer than my average landing.
_______ average.
_______ harder than my average landing.
_______ harder than my hardest landing.

If you were wearing ankle braces and/or knee braces or landed on the viscoelastic padding during your jump, please answer the following questions carefully.

I jumped under the following legwear condition(s):
(Select more than one answer if applicable.)

________ ankle braces.
________ knee braces.
________ viscoelastic padding on force plate.

The above legwear condition(s) made moving around (walking/assuming pre-jump posture) before I made my jump off the platform ______. **(Do not answer if you jumped on the viscoelastic padding.)**
(Select one description.)

_____ easier
_____ more difficult
_____ no different than usual

The above condition(s) made my initial landing on the force plate ______.
(Select one description.)

_____ easier
_____ more difficult
_____ no different than usual

The above legwear condition(s) made my roll/twist when performing the PLF ______.
(Do not answer if you jumped on viscoelastic padding.)
(Select one description.)

_____ easier
_____ more difficult
_____ no different than usual

APPENDIX D

EXPERIMENT I POST-STUDY QUESTIONNAIRE

EXPERIMENT I POST-STUDY QUESTIONNAIRE

Post-Study Questionnaire

Subject Number:___________ Date:__________

All test participants please answer the following questions:

1. This is a question about the PLFs you perform during actual jumps.
When I perform a PLF , I prefer to land ______ provided the wind was in my favor. (Select one answer.)

_______ in a right PLF.
_______ in a left PLF.
_______ in either a right or left PLF (no preference).

Based on your jumps in this study:

2. Please rank the following legwear conditions using the numbers 1- 5 (1=*Best* to 5=*Worst*) for the different criteria listed below. (Use a ranking number only once in each column and note that the Comfortable to Wear column has only 4 legwear conditions to rank.)

Comfortable to Wear	**Leg Support during landing**	**Aids Proper PLF Posture**
____ Boots Only	____ Boots Only	____ Boots Only
____Boots/Ankle Braces	____Boots/Ankle Braces	____Boots/Ankle Braces
____Boots/Knee Braces	____Boots/Knee Braces	____Boots/Knee Braces
____Boots/Ankle/Knee Braces	____Boots/Ankle/Knee Braces	____Boots/Ankle/Knee Braces
	____Viscoelastic Padding	____Viscoelastic Padding

3. If you were performing PLFs during missions or training what legwear combination would you prefer? Using the numbers 1 to 5 (1=First preference and 5=Last preference), please rank the five legwear conditions according to your preference for wear. (Each number should be used only once and the legwear ranking should be based on the equipment used in this study.)

____Boots Only

____Boots/Ankle Braces

____Boots/Knee Braces

____Boots/Ankle/Knee Braces

____Viscoelastic Padding (probably in the form of boot inserts or padding added to the boot soles)

4. If a cushioning/bracing device is designed for use by airborne troops, what features do you think it should have? Give a rating for each feature listed below using the following ratings :
1=necessary *2=optional* *3=unnecessary.*

a. Adjustable Fit ____ b. Easy to Don/Remove____ c.Portable/Light____

Subject Number:___________ Date:__________

4. Continued.
Give a rating for each feature listed below using the following ratings:

1=necessary *2=optional* *3=unnecessary.*

d. Water Resistant____ e. Reusable____ f. Easy to Clean____

g. NBC Features____ h. Camoflagued____ i. Disposable____

j. Ventilated/Breathable Material____

k. Foot cushioned____ l. Ankle padded____ m. Knee padded____

n. Boot insert cushions____ o. Inflatible cushioning around ankle/calf (pump action)____

p. Restrict knee bend____ q. Restrict ankle bend____ r. Restrict knee twist____

s. Restrict ankle twist____ t. Promotes initial toe touchdown ____

5. Please list other features which you would like to have in the cushioning/bracing device. Add any drawing or explanation of these features if you desire.

6. In what ways was your landing in this study different than a landing from a real parachute jump? (Please explain.)

APPENDIX E

EXPERIMENT II POST-JUMP QUESTIONNAIRE

EXPERIMENT II POST-JUMP QUESTIONNAIRE

Post-Jump Questionnaire

Subject Number:__________ Jump Height:________ Date:_________

Please answer the following questions about the PLF landing you just completed:

Rate the hardness of your landing by circling the appropriate number. (Note: The number 5 rating corresponds to landing hardness when you jumped on the rubber padded force plate from the same height.

0	1	2	3	4	5	6	7	8	9	10
Softest Landing					Landing on Padded Force Plate from same Jump height (Boots only)					Hardest Landing

I jumped under the following legwear condition (select one):

________ ankle braces.
________ ankle braces + **Poron** damping soles. **P**
________ ankle braces + **Poron** + **Sorbothane** damping soles. **S**
________ ankle braces + **Poron** + **Akton** damping soles. **A**
________ ankle braces + **EVA** damping soles. **E**

The above legwear condition made moving around (walking/assuming pre-jump posture) before I made my jump off the platform ______.
(Select one description.)
_____ easier
_____ more difficult
_____ no different than usual

The above condition made my initial landing on the force plate ______.
(Select one description.)
_____ easier
_____ more difficult
_____ no different than usual

The above legwear condition made my roll/twist when performing the PLF ______.
(Select one description.)
_____ easier
_____ more difficult
_____ no different than usual

APPENDIX F

EXPERIMENT II POST-STUDY QUESTIONNAIRE

EXPERIMENT II POST-STUDY QUESTIONNAIRE

Post-Study Questionnaire

Subject Number:___________ Date:__________

Please answer the following questions:

1. This is a question about the PLFs you perform during actual jumps.
When I perform a PLF , I prefer to land ______ provided the wind was in my favor. (Select one answer.)

_______ in a right PLF.
_______ in a left PLF.
_______ in either a right or left PLF (no preference).

Based on your jumps in this study:

2. Please rank the following legwear conditions using the numbers 1- 3 (1=*Best* to 3=*Worst*) for wear comfort. (Use a ranking number only once .)

Comfortable to Wear

____ Boots Only

____Boots/Ankle Braces

____Boots/Ankle Braces/Damping Heels

3. Rate each legwear on the ability to aid proper PLF posture during landing. Circle the appropriate rating number on the scale. **(Note: The number 3 for "no change" should correspond to the effects of jumping in boots only.)**

Legwear: Boots + Ankle Braces

1 2 3 4 5
Harmful No Change Useful

Legwear: Boots + Ankle Braces
+ **Poron** soles **P**

1 2 3 4 5
Harmful No Change Useful

Legwear: Boots + Ankle Braces
+ **Poron/Sorbothane** soles **S**

1 2 3 4 5
Harmful No Change Useful

Legwear: Boots + Ankle Braces
+ **Poron/Akton** soles **A**

1 2 3 4 5
Harmful No Change Useful

Legwear: Boots+Ankle Braces
+ **EVA** soles **E**

1 2 3 4 5
Harmful No Change Useful

4. If you were performing PLFs during missions or training what legwear combination would you prefer? Using the numbers 1 to 6 (1=First preference and 6=Last preference), please rank the six legwear conditions according to your preference for wear. (Each number should be used only once and the legwear ranking should be based on the equipment used in this study.)

____Boots Only

____Boots/Ankle Braces

____Boots/Ankle Braces/**Poron** soles **P**

____Boots/Ankle Braces/**Poron** + **Sorbothane** soles **S**

____Boots/Ankle Braces/**Poron** + **Akton** soles **A**

____Boots/Ankle Braces/**EVA** soles **E**

5. Did the braces provide support to your ankles during landing? _____Yes_____No

6. Do you think that some type of ankle bracing is necessary for paratroopers?_____Yes_____No

7. If a cushioning/bracing device is designed for use by airborne troops, what features do you think it should have? Give a rating for each feature listed below using the following ratings :
1=necessary *2=optional* *3=unnecessary.*

a. Adjustable Fit ____ b. Easy to Don/Remove____ c. Portable/Light____

d. Water Resistant____ e. Reusable____ f. Easy to Clean____

g. NBC Features____ h. Camoflagued____ i. Disposable____

j. Ventilated/Breathable Material____

k. Foot cushioned____ l. Ankle padded____ m. Knee padded____

n. Boot insert cushions____ o. Inflatible cushioning around ankle/calf (pump action)____

p. Restrict knee bend____ q. Restrict ankle bend____ r. Restrict knee twist____

s. Restrict ankle twist____ t. Promotes initial toe touchdown ____

8. Please list other features which you would like to have in the cushioning/bracing device. Add any drawing or explanation of these features if you desire.

9. In what ways was your landing in this study different than a landing from a real parachute jump? (Please explain.)

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