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BIOMECHANICAL ANALYSIS OF MILITARY BOOTS: PHASE III

Recommendations for the Design of Future Military Boots

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13. ABSTRACT *(Maximum 200 words)*

This report contains a series of recommendations for the design of future military footwear. The recommendations relate to shock attenuation, midsole stiffness, medio-lateral stability, and upper construction. Approaches for implementing the recommendations, including material selection and construction techniques, are discussed. The recommendations are based upon findings from a two-phase research program to assess the biomechanical properties of boots presently used by military personnel. The military boots used in the research were the black leather combat boot and the hot weather boot. Commercial sport shoes and boots also were tested. These included a cross trainer, a work boot, a basketball shoe and a hiking boot. In Phase I, the military and commercial footwear items were subjected to materials tests that included measures of impact, flexibility, stability, resistance of the outer sole to wear, water penetration, and frictional properties of the outsole. In Phase II, men and women wore the footwear while walking, marching, running, jumping from heights and running an agility course. The data acquired included ground reaction forces, in-shoe pressures, sagittal plane kinematics, rearfoot movement, leg muscle activity, metabolic rate, and heart rate. The findings from Phase I (NATICK/TR-93/006), and Phase II VOL I (NATICK/TR-96/011) and Phase II VOL II (NATICK/TR-96/012) are summarized and presented with the recommendations.

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PREFACE

The report on the recommendations for future military boots is the final report of a project carried out under U.S. Army Soldier Systems Command, Natick Research, Development and Engineering Center contract DAAK60-91-C-0102. The work was performed at the Biomechanics Laboratory, Department of Exercise Science, University of Massachusetts, Amherst, MA. Dr. Carolyn K. Bensel was the project officer for the contract. Dr. Bensel is affiliated with the Behavioral Sciences Division, Science and Technology Directorate. This project is part of the 6.2 program 1L162723AH98AAKOO (Aggregate Code T/B1368) -- Biomechanical Approach to Soldier-CIE Integration, which is being carried out by Dr. Bensel and other members of the Behavioral Sciences Division.

The references for the other reports in this series are:

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BIOMECHANICAL ANALYSIS OF MILITARY BOOTS
Phase III: Recommendations for the Design of Future Military Boots

INTRODUCTION

The most widely issued footwear in the Army and the Marine Corps is a boot designated for use in training, garrison, and field environments when specialized footwear (e.g., safety shoes, cold weather boots, hot weather boots) is not needed. Male and female recruits receive this boot at the beginning of their basic military training and use it for almost all activities that comprise "boot camp". Recruits are sometimes permitted to wear commercial sport shoes, which they bring with them from home or purchase after arriving for training. The sport shoes are worn only to a limited extent, generally for portions of the formal physical training program, such as daily calisthenics and runs, although these activities may also be performed in the boot. After completing basic training, military men and women continue to wear the boot for physical training, field exercises, in their garrison work environments, and on the battlefield.

There have been a number of generations of this footwear, each differing from the others in design and material composition. The latest version was introduced into the military inventory in the mid-1980s. This boot, commonly referred to as the "combat boot", has a leather upper. The outsole is direct molded to the upper and has a deep lug design. The boot is issued with a removable, urethane foam insert that has a fiberboard backing and extends from the heel to the toe of the boot.

Development of the latest combat boot began in the early 1980s at the U.S. Army Natick Research, Development and Engineering Center. The development effort was guided by requirements, or performance criteria, that were generated by Army and Marine Corps organizations responsible for identifying the characteristics that materiel must embody to meet the needs of military personnel. The military wanted a boot that enhanced the locomotor capabilities of the wearer, minimized the occurrence of lower extremity problems, and was comfortable. Other requirements pertained to weight, height, design of the closures, camouflage characteristics, water-resistance, durability, storage life, military appearance, and outsole composition. Still other requirements dealt with cost of the item, production rate, and production capabilities within the United States. Indeed, much was demanded of the footwear, and the boot reflects the attempt to accommodate a range of requirements at a relatively low cost.

In addition to the combat boot, there is another boot that is frequently worn by many Army and Marine Corps personnel, although this boot is not as widely used as the combat boot. The second footwear item, which was developed during the 1960s for use in Southeast Asia, is commonly referred to as the "jungle boot". This boot is now prescribed for use in hot-humid climates, but soldiers are given the option of wearing it in other climates should they so choose. Like the combat boot, it is worn for physical training, field exercises, in garrison, and on the battlefield. The jungle boot is fabricated of leather in the foot portion and has a cotton/nylon duck upper. The boot has a direct molded sole with a lug tread and a steel plate incorporated into the insole. Like the combat boot, the jungle boot is issued with a removable insert. As was the case with the combat boot, development of the jungle boot was guided by requirements of the military users. For example, the upper is made of duck because of a requirement for the boot to dry quickly; eyelets are in the arch area because some means for water to drain out of the boot was required; and the steel plate serves a requirement for protection of the foot from puncture by spikes embedded in the ground.

The growing interest of the public in physical fitness over the last 15 or 20 years, and the attention paid by footwear manufacturers to this expanding market, has stimulated research into materials and construction processes for athletic footwear. Much of this research has been in the realm of sport biomechanics (Cavanagh, 1980; Nigg, 1986b). Goals of the biomechanics research done on athletic footwear include enhancing the locomotor performance of the wearer and reducing the incidence of lower extremity injuries (Cavanagh, 1980; Nigg, 1986b). There is evidence that progress has been made in achieving these goals (Cavanagh, 1980; Nigg, 1986a). Although the military services also have an interest in enhancing the locomotor performance of personnel and reducing lower extremity injuries (Bensel, 1976; Bensel and Kish, 1983), findings from biomechanical studies have not yet been systematically employed in the development of military boots.

Given the lack of information about the biomechanical properties of current military boots and the potential for improving the boots in the future through application of biomechanical principles, a research program focusing on the biomechanical analysis of military footwear was established. The research was comprised of a materials testing phase and a human user testing phase. These phases of the program have been completed (Hamill and Bensel, 1992, 1996a, 1996b).

The footwear studied in this research effort included the combat and the jungle boots and a variety of commercial sport shoes and boots. The military boots were developed to meet many requirements. In addition to the goals of enhancing the mobility of the wearer and minimizing the occurrence of lower extremity injury during performance of a wide variety of activities on a wide range of surfaces and terrains, cost, storage life, and myriad other factors influenced the decisions that led to the versions of the combat and the jungle boots used in this research. The decisions included trade-offs, where some factors were sacrificed for others. No doubt, it can also be said that the design of the commercial items tested here emanated from consideration of many factors in addition to the performance efficiency and lower extremity health of the wearer, although the factors may have been different from those influencing military boot development. It is likely that these decisions also included trade-offs in arriving at the finished item. Thus, as is the case for the military footwear, the commercial items do not represent the "ideal" footwear. Furthermore, the commercial footwear items are not appropriate for use as military field boots. However, the commercial items can be viewed as "models" against which to assess the characteristics of the military boots.

An objective of the research was to develop, from the data acquired, a series of recommendations for future military footwear with regard to materials, design, construction, fabrication techniques, and any other features that would benefit the performance and the lower extremity health of military personnel, particularly ground troops. The recommendations arising out of the research are presented in this report. Also included here are summaries of the materials and the human user testing.

PHASE I: MATERIALS TESTING

Footwear Tested

Hamill and Bensel (1992) carried out the materials testing phase of the research on the combat and the jungle boots and six types of commercial sport shoes and work boots. The combat and the jungle boots were selected for study because they are general-purpose footwear items and are widely used throughout the Army and the Marine Corps.

The commercially available items under study were not developed for use as military field footwear. However, they do incorporate materials and design concepts which, if proven to be beneficial to the performance and the lower extremity health of the wearer, could be adapted to a military boot. Thus, the commercial items were included in this study in order to acquire information on their performance characteristics. The testing of the commercially available footwear also served to generate data against which to assess the findings for the military footwear.

The six types of commercial footwear items studied by Hamill and Bensel (1992) in the materials testing phase were: the Nike Air Max, a Nike cross trainer, a Red Wing work boot, the Reebok Pump, a Rockport hiking boot, and a Rockport walking shoe. These commercial items, along with the combat and the jungle boots, were subjected to tests of flexibility, stability, sole wear, water penetration, outsole friction, and impact. Samples of each footwear type were tested new, in an unworn state, and additional samples were tested in the same manner after having been worn outside the laboratory by men and women for approximately 40 days. The procedures employed for the materials testing followed those used by Cavanagh (1978; Cavanagh and Williams, 1981), with some modifications in apparatus and protocols.

Description of Tests and Summary of Findings

Flexibility

The flexibility test was carried out on a device that has two platforms connected by a hinge. The shoe is positioned relative to the two platforms such that a point 40% of the shoe length, as measured back from the toe, is aligned with the hinge between the platforms. It is at this hinge that flexion occurs during the test. A load cell is mounted on the device to measure the force of the resistance to flexing.

Flexibility is considered to be an important parameter influencing the human/footwear system. The less flexible the footwear, the more force the muscles of the foot and leg must apply to bend the shoe in order to propel the body into the next step. Therefore, the less flexible the footwear, the more the muscles may be stressed (Cavanagh, 1980).

Hamill and Bensel (1992) found that the military boots were among the least flexible of the footwear items studied. This was the case whether the footwear was tested in an unworn or in a worn state. The stiffest of the items tested was the Red Wing work boot, which required more than double the amount of force to bend than the most flexible shoe, the Nike Air Max. The military boots were between the extremes defined by the Red Wing and the Air Max.

Stability

Like the flexibility test, the stability test can be viewed as a measure of material stiffness. In the case of the flexibility test, the forepart of the shoe is assessed; in the stability test, the focus is on the medial and the lateral borders of the shoe in the heel area. The device used for testing again consists of two, hinged platforms, one fixed and the other movable. The shoe is fixed in position on the device such that approximately 1 cm of the heel portion lies on the movable platform and the rest of the shoe lies on the fixed platform. The movable platform is displaced compressing the sole at the heel border. A load cell measures the force necessary to displace the movable platform and a potentiometer measures the angular distance moved.

After the landing impact at initial contact of the foot with the ground, there is pronation at the subtalar joint within approximately the first 50% of the foot contact period, followed by supination until toe-off (Clarke, Frederick, and Hamill, 1984). Although the movements of the subtalar joint act to decrease peak forces experienced after foot strike, excessive pronation has been linked to running-related injuries, particularly those of the knee (Clarke et al., 1984). Harder midsoles have been found to decrease the amount of pronation and rearfoot movement during running (Cavanagh, 1980; Clarke, Frederick, and Hamill, 1983). Therefore, higher values on the stability test, indicating greater forces required to compress the midsole, reflect better rearfoot control in the footwear.

Hamill and Bensel (1992) reported that the Nike Air Max and the Nike cross trainer had among the lowest scores on the stability test. On the other hand, the combat boot and the jungle boot, along with the Red Wing work boot, had the highest scores for stability at both the medial and lateral borders. This was found regardless of whether the footwear was tested in an unworn or in a worn state.

Sole Wear

For the sole wear test, the shoe is fixed over an abrasive belt in a position representative of foot strike for a runner. A jig maintains this position in which the rear outside border of the heel is closest to the abrasive surface and the shoe is weighted to ensure that contact is maintained between the shoe and the belt. The belt is moved past the shoe for periods of 15 s and the outsole is measured after each period. Testing of the shoe is terminated when the depth to which the outsole has been penetrated equals or exceeds 1.9 cm. The score on the test is the total time required to achieve the penetration of 1.9 cm, expressed in 15-s increments.

Obviously, the higher the score on the sole wear test, the better from an economic standpoint. However, the decreases in outsole thickness with wear can also be associated with reduction in the shock-absorbing properties of the footwear. In addition, sole wear can change the alignment of the foot and leg during ground contact, possibly resulting in lower extremity injury (Cavanagh, 1980).

Hamill and Bensel (1992) found that the Nike Air Max and the Reebok Pump, which were low in stiffness as measured on the flexibility test, took longer to reach the criterion level on the sole wear test than the other footwear types. On the other hand, the Red Wing work boot and the combat boot, which were relatively high in stiffness, wore down quickly compared with the other footwear types tested.

Water Penetration

For the water penetration test, the shoe is mounted on a footwear last that is instrumented with water-sensitive electrodes. The footwear is submerged in water for approximately 15 min. Each electrode is sampled once every 15 s throughout the immersion period. The measure on this test is the length of time until water is first detected at any one of the electrode sites. In those cases in which water is not detected during the immersion period, a score equal to the total time of immersion is assigned.

The water penetration test is a measure of the ease with which water can pass from the outside environment into the footwear. Higher scores indicate better resistance to water penetration. This is a desirable physical characteristic in footwear for military users because military personnel must often work in wet environments where water intrusion can precipitate serious foot problems (Orr and Fainer, 1952).

Hamill and Bensel (1992) found that the interior of the combat boot remained dry during the 15-min. immersion period. This was the case whether the item was tested in an unworn state or after having been worn outside the laboratory for a period of time.

The other footwear items with all-leather uppers also performed well. On the other hand, water entered the jungle boot quickly, because of the screened eyelets set in the leather portion of the boot upper. When retested after the eyelets had been plugged, the interior of the jungle boot remained dry throughout the immersion period.

Outsole Friction

The frictional characteristics of the outsoles of the footwear items were tested using a towed-sled procedure similar to that proposed by Irvine (1967). For this procedure, a Chatillon gauge with a known normal force is employed. The portion of the footwear being tested is bolted to the underside of a sled and the gauge is connected to the sled. The gauge is pulled manually along a horizontal surface at a constant velocity. A static coefficient of friction (COF) is calculated from the pull force at the point of movement and a dynamic COF is calculated from the pull force during the constant motion. The higher the COF, the greater the resistance of the footwear item to slipping. The footwear items were tested on asphalt, carpeting, cement, natural grass, and vinyl tile. Each surface was used under four treatment conditions: dry, wet, oiled, and greased.

The apparatus employed involves movement straight ahead at a constant speed, such as that seen in walking or running. When a human is moving in this manner, a higher COF between the footwear and the surface is desirable in order to avoid slipping (Cavanagh and Williams, 1981). A number of researchers have cited static and dynamic COFs of 0.30 as being the lowest acceptable levels (Cavanagh and Williams, 1981; Perkins and Wilson, 1983). In terms of a maximum COF, it has been stated that values greater than 0.80 may constitute a trip hazard (R. O. Andres, personal communication, February 1992).

Hamill and Bensel (1992) reported that all the footwear items tested had static and dynamic COFs of at least 0.29, except on cement and tile surfaces treated with oil or with grease. This was the case whether the footwear was tested in an unworn state or after it had been worn outside the laboratory. Thus, it can be said that the military boots and the other footwear items tested had acceptable frictional characteristics on most surfaces. Also, relative to the commercial items, the combat boot and the jungle boot generally did not have particularly high or low COFs.

Impact

An impact tester (Exeter Research Impact Tester) was used to assess impact and rebound. This instrument consists of a metal shaft, or missile, that slides freely in the vertical plane. The missile head attached to the metal shaft is a solid, metal cylinder.

The footwear being tested is fixed in place below the shaft. A linear variable differential transducer and a Kistler accelerometer return the data on each drop of the missile to a computer. In the context of the human/footwear system, the impact tester is intended to mimic the foot hitting the ground at foot strike.

A number of parameters are measured directly or derived on the impact test. They include peak g, the maximum acceleration of the missile head upon impacting the shoe. In terms of the human/footwear system, peak g is used as an index of the vertical force occurring at initial contact of the foot with the ground. The contact results in an impulsive force that, during running, may be two to three times greater than the human's body weight (Cavanagh and LaFortune, 1980; Clarke, Frederick, and Cooper, 1983). In the impact test, peak g is interpreted as a reflection of the shock-absorbing capabilities of the shoe, with lower values indicating better shock absorbency (Cavanagh, 1980).

Time to peak g is also measured during impact testing. This is the time from first contact of the missile head with the shoe to achievement of maximum deceleration. The higher the value on this measure, the lower is the rate of change of the impact force. In terms of the human/footwear system, a lower rate of change of the impact force indicates a slower deceleration of the foot as it contacts the ground and, thus, less of a jolt to the body (Clarke, Frederick, and Cooper, 1983). Longer times to peak g on the impact test are thought to indicate better cushioning in the shoe (deMoya, 1982).

The coefficient of restitution, the negative ratio of the relative velocity after impact to the relative velocity before impact, is another parameter measured on the impact test. The higher the coefficient of restitution, the greater the amount of kinetic energy conserved upon impact. In terms of the human/footwear system, the less energy lost upon impact, the less internal energy the human must use to propel the body into the next step (Clarke, Frederick, and Cooper, 1983). In footwear materials testing, the coefficient of restitution is used as an index of the cushioning properties of the footwear with higher values indicating better cushioning (deMoya, 1982). Energy return is the coefficient of restitution multiplied by 100. The energy return parameter serves to emphasize the fact that 100% of the kinetic energy is conserved in a perfectly elastic impact and 0% of the energy is conserved in a completely inelastic impact. As is the case for the coefficient of restitution, higher energy return values indicate better cushioning of the footwear (deMoya, 1982).

Hamill and Bensel (1992) found that the impact test revealed the greatest differences between the military and the commercial footwear, whether the items were tested in an unworn state or after a period of wear outside the laboratory. The best overall findings on this test were associated with the Nike Air Max and the Nike cross trainer. Those shoes reduced the peak g and the peak pressure by approximately 50%

compared with the military boots. With the Nike Air Max and the Nike cross trainer, peak g and peak pressure were also reduced by some 30% to 40% compared with the Red Wing, a commercial work boot that, of the commercial footwear tested here, had impact characteristics most similar to those of the military boots. Furthermore, shorter times to peak g, indicating a greater jolt to the body upon impact, were obtained with the military boots and the Red Wing than with the Air Max and the cross trainer. Therefore, in terms of the human/footwear system, greater impact forces experienced over a shorter time period would be expected when the combat boot, the jungle boot, or the Red Wing are being worn compared with the situation when the Air Max or the cross trainer are being used.

Whether tested in an unworn or a worn condition, the Nike cross trainer had particularly high values for coefficient of restitution and energy return compared with the values for the military boots. In the context of the human/footwear system, more energy would be lost upon ground impact and, thus, more internal energy would be required to propel the body forward with the military boots than with the cross trainer.

Footwear Mass

Another consideration related to energy expenditure is the mass of footwear. A number of research studies have found that there is a 0.7% to 1.0% increase in the energy cost of locomotion for each 100-g increase in the weight of the footwear, per pair, being worn (Jones, Toner, Daniels, and Knapik, 1984; Jones, Knapik, Daniels, and Toner, 1986; Martin, 1984). The military boots were the heaviest footwear items of all those tested in the present study, and the combat boots increased in weight over the wear period.

PHASE II: HUMAN USER TESTING

Footwear Tested

Hamill and Bensel (1996a, 1996b) carried out the human user testing phase of this research on the combat and the jungle boots and four of the six types of commercial footwear that had been included in the materials testing phase. The two types of commercial footwear that were not included in this phase were the Nike Air Max and the Rockport walking shoe. In the materials testing phase, the Nike Air Max yielded results on the impact test that were similar to those for the Nike cross trainer (Hamill and Bensel, 1992). In addition, the height of the cross trainer, measured from the heel breast to the top of the upper, is greater than the height of the Air Max and more closely approximates the height of a boot upper. Therefore, the Nike cross trainer was selected for further testing and the Nike Air Max was not. The Rockport walking shoe was not selected for this second phase of testing because, aside from poor abrasion resistance on the outsole wear test, the shoe did not evidence particularly good or bad performance characteristics. Also, like the Nike Air Max, the Rockport walking shoe has a low upper compared with the other military and commercial footwear items included in this research. All footwear types that Hamill and Bensel (1996a, 1996b) included in the human user testing had uppers that extended to the level of the lateral malleolus or higher. These high-top designs tied together the actions of the lower leg, the ankle, and the foot. Thus, the uppers of all the footwear items served similar functions.

Independent and Dependent Variables

Both men and women participated in the human user testing. They wore the two types of military boots and the four types of commercially available footwear while performing a number of physical activities in a laboratory setting. The activities performed by the participants included walking at 1.15 m/s, marching at 1.50 m/s, and running at 3.40 m/s. These locomotor movements were carried out overground to generate kinetic, kinematic, and electromyographic (EMG) data and on a treadmill to generate metabolic and heart rate data. Regardless of whether performing overground or on a treadmill, the participants were required to maintain the same pace for a given locomotor movement. However, the duration of the movements differed. Movement overground required seconds to complete. On the treadmill, a movement was performed for 7 min. in order to generate steady-state metabolic and heart rate data (Stainsby and Barclay, 1970).

The kinetic data acquired during overground walking, marching, and running consisted of ground reaction force-time histories as measured with a force platform. Ground reaction is the force in reaction to the push transmitted to the ground by the foot during ground contact. It reflects the acceleration of the total body center of gravity

(Miller, 1990). During the locomotor movements in this study, forces were recorded throughout a contact, or support, phase. That is, recording began at the time of foot strike, or initial contact of the foot with the ground, and continued through toe-off, or termination of contact of the foot with the ground. The three force components measured were vertical force, antero-posterior force, and medio-lateral force.

Of the three force components, the vertical ground reaction force has been found to be the largest in magnitude during such locomotor movements as walking, marching, and running (Cavanagh and Lafortune, 1980). Research has shown that the amplitude of vertical ground reaction force increases with increases in speed (Munro, Miller, and Fuglevand, 1987). The amplitude of vertical ground reaction force during running is up to twice that occurring during walking (Cavanagh and Lafortune, 1980). Furthermore, the magnitudes of the vertical forces during running are quite high. Cavanagh and Lafortune (1980) reported vertical forces of two to three times body weight at running speeds in the range of 4.12 m/s to 4.87 m/s.

The repeated exposure of the body to these high loads every time the foot strikes the ground during locomotion has been implicated in the occurrence of musculoskeletal disorders, particularly overuse injuries (James, Bates, and Osternig, 1978). Researchers have found that, as a means of protection from injury, the body may make kinematic adjustments to mitigate the impact forces during ground contact (Clarke, Frederick, and Cooper, 1983; Frederick, Clark, and Hamill, 1984; Nigg, Bahlsen, Denoth, Luethi, and Stacoff, 1986).

One kinematic adjustment reported by Clarke, Frederick, and Cooper (1983) is increased knee flexion following foot strike. According to Miller (1990), ground reaction forces may not be sensitive to such compensatory mechanisms because ground reaction forces reflect the acceleration of the total body center of gravity. Therefore, kinematic data must be acquired and linked to the kinetic data. This was done in the present study through the recording of sagittal plane kinematics during overground walking, marching, and running. Motions at the knee, as well as at the hip, the ankle, and the metatarsal joints, were analyzed as a function of the type of footwear worn. Miller (1990) and others (Cavanagh, 1980; Cavanagh, Valiant, and Misevich, 1984; Milliron and Cavanagh, 1990; Nigg, 1986b) have pointed out a further limitation of ground reaction force data: These data reveal the magnitude of the forces, but not their distribution. Furthermore, the pressure distribution of primary interest is at the shoe/foot interface, not the shoe/ground interface (Cavanagh et al., 1984). To answer this need, arrays of pressure transducers have been developed that can be placed in the shoe (Cavanagh et al., 1984). This technique for acquisition of information on pressure distribution was used in the present study during overground walking, marching, and running.

In addition to the kinematic adjustment of increased knee flexion following foot strike with increases in shoe hardness (Clarke, Frederick, and Cooper, 1983; Nigg et al., 1986), another kinematic mechanism for decreasing the peak forces to which the body is exposed immediately following foot strike is pronation of the subtalar joint (Clarke, Frederick, and Hamill, 1983; Nigg et al., 1986; Nigg, Bahlsen, Luethi, and Stokes, 1987). After foot strike, there is pronation within approximately the first 50% of the contact phase, followed by supination until toe-off (Clarke et al., 1984). Pronation of the subtalar joint consists of simultaneous calcaneal eversion, forefoot abduction, and ankle dorsiflexion. Supination involves the reverse movements of inversion, adduction, and plantar flexion (Hlavac, 1977). Although the movements of the subtalar joint act to decrease peak forces experienced by the body after foot strike, excessive pronation has been linked to injuries, particularly those of the knee and the Achilles tendon (Hlavac, 1977; James et al., 1978).

A common means of quantifying rearfoot movement is digitization of film records to measure the relative movement of the calcaneus and the lower leg during a locomotor activity. The amount of eversion of the calcaneus is considered to be a predictor of the amount of pronation that is occurring (Clarke et al., 1984). This approach was used in the present study to analyze rearfoot movement during overground walking, marching, and running in the various types of military and commercial footwear.

Two additional classes of dependent measures were included in this study. These were EMG data recorded from muscle groups of the leg during overground movements and physiological data recorded during treadmill movements. Electromyography has been used as a method for studying the mechanisms controlling locomotion (Arsenault, Winter, and Marteniuk, 1986; Mann, Moran, and Dougherty; 1986; McClay, Lake, and Cavanagh, 1990). It has been found that, when a subject's velocity is constant, there is a highly repeatable pattern of muscle function for that subject, but there may be extreme differences between subjects (Arsenault et al., 1986).

The physiological measures recorded in the present study during treadmill walking, marching, and running were submaximal oxygen consumption and heart rate. Both measures have been found to be affected by variations in the weight carried on the feet, although oxygen consumption appears to be the more sensitive of the two (Jones et al., 1984; Martin, 1985). Non-weight related effects on oxygen consumption have also been demonstrated. Frederick (1984, 1986) reported that systematically altering the hardness of shoe materials, with shoe weight held constant, causes adjustments in oxygen consumption during running. He found that the softer shoes were associated with lower oxygen uptake.

In addition to overground and treadmill walking, marching, and running, the men and women in the present study performed jumps from platforms of two different heights, 0.32 m and 0.72 m, onto the ground. Kinetic and kinematic measures, similar to those captured during overground locomotion, were recorded during these jump/landings. The kinetic data consisted of ground reaction force-time histories as measured with a force platform on which the subjects landed. In-shoe sensors were used to measure pressure distributions between the plantar surface of the foot and the footwear. Sagittal plane and rearfoot movement kinematics were also recorded during the jump/landings, as was electromyographic activity of leg muscles.

McNitt-Gray (1991) found that peak vertical ground reaction forces in a drop from 0.72 m are approximately six times body weight, and, in a drop from 1.28 m, exceed nine times body weight. These data suggest a potential for injury during landings. However, as in overground locomotion, kinematic adjustments are made that may protect the body from injury (McNitt-Grey, 1991).

The subjects in the present study also performed an agility course run, with time to course completion as the dependent measure. The course was similar to one used by Robinson, Frederick, and Cooper (1986). It included 90° and 180° changes in direction, sprinting, back pedaling, stepping to the side, starting, and stopping. Robinson et al. (1986) used the course to examine the effects of the restrictive characteristics of a shoe upper on performance. The footwear used was a high-top basketball shoe. Systematic changes in ankle support were accomplished by placing sets of four stiffeners in pockets on the shoe, immediately anterior and posterior to the lateral and medial malleoli. Subjects completed the agility course without any stiffeners in the shoe and with three sets of stiffeners, each set having a different stiffness achieved through varying material modulus. The fastest course times were achieved when stiffeners were not used and the slowest when the stiffeners with the highest bending moment were used. Robinson et al. (1986) concluded that the stiffeners restricted normal ranges of motion in the ankle, inhibiting the leg from obtaining positions of mechanical advantage and thus decreasing the speed of maneuvering.

As has been mentioned, the men and women participating in the present research performed the locomotor movements, jump/landings, and agility course runs in the two types of military boots and the four types of commercially available sport/work shoes. In addition to the footwear variable, a load variable was introduced with participants being tested with and without Army load-carrying gear. Kinoshita (1985) collected both kinematic and kinetic data on the effects of loads on men's walking gait. He found that ground reaction force increased in proportion to the increase in load. The kinematic data revealed greater knee flexion immediately after foot contact with the heavier load, a means of reducing the magnitude of the impact force. The foot also rotated in an antero-posterior direction around the distal ends of the metatarsal bones for a longer period of time when the heavier load was carried.

The load-carrying equipment used in this study consisted of the Army's fighting and existence loads. The basic components of the fighting load are a tactical load-bearing vest and an equipment belt. The fighting load was weighted to total 9.1 kg (20.0 lb). The basic component of the existence load is a large backpack with an internal frame. Two existence loads were configured for this research. For one load, plastic bottles of water and lead weights totalling 10.2 kg (22.5 lb) were put in the pack bag to bring the total mass of the backpack, including the mass of backpack components, to 13.6 kg (30 lb). For the other existence load, the mass of the items in the pack bag was increased to 19.3 kg (42.5 lb), resulting in a total backpack mass of 22.7 kg (50 lb). Male participants were tested without load-carrying gear (load of 0 lb), with the fighting load and the 13.6-kg existence load (total load of 50 lb), and with the fighting load and the 22.7-kg existence load (total load of 70 lb). The women were tested under only two levels of the load variable, 0 lb and 50 lb.

In the Army, the same footwear items are used by new recruits, many of whom are being exposed for the first time to a regular physical training regimen, and by career personnel, who have engaged in fitness training for some years. Thus, the men and women selected as participants in this study represented a range of fitness levels. Both the men and the women were divided into three fitness groups, low, medium, and high fitness, on the basis of aerobic capacity as measured by a test of maximal oxygen uptake. Five men and five women were assigned to each fitness level.

In the statistical treatment of the data, the data of the men and the women were treated separately as was each of the dependent measures. The form of the analysis of the men's data was: Footwear (combat boot, jungle boot, Reebok Pump, Nike cross trainer, Rockport hiking boot, Red Wing work boot) by Load (0 lb, 50 lb, 70 lb) within Fitness Group (low, medium, high). The form of the analysis of the female data was the same as that of the men's, with the exception of there being two, instead of three levels of the load factor.

Summary of Findings

Fitness

Hamill and Bensel (1996a, 1996b) found that few of the analyses of the dependent measures yielded a significant main effect of fitness. The significant differences among fitness groups were essentially limited to electromyographic responses during marching and the 0.72-m jump/landing. Furthermore, the few significant effects did not reveal consistent relationships among fitness levels. Hamill and Bensel reported that, on the locomotor movements and, to a lesser extent, on the jump/landings, fitness interacted with load to significantly affect many of the parameters of ground reaction force and sagittal plane kinematics.

Load

In addition to interacting with fitness to affect locomotor and jump/landing performance, load had a significant main effect on many of the dependent variables (Hamill and Bensel, 1996a, 1996b). Oxygen consumption and heart rate during the locomotor movements generally increased with increases in load weight. During walking and marching, but not during running, first maximum forces of the vertical ground reaction force component increased with load; second maximum vertical force increased with load during all three locomotor movements, as did average vertical force and total vertical impulse.

In analyzing body kinematics as affected by load, Hamill and Bensel (1996a, 1996b) found that maximum knee flexion during walking and marching increased with load, although the effect was not significant. However, a number of kinematic measures recorded during the locomotor movements did yield a significant main effect of load, including maximum ankle plantarflexion, maximum ankle dorsiflexion, and maximum metatarsal flexion.

Footwear

In comparing the performance of the footwear items included in the human user testing, Hamill and Bensel (1996a, 1996b) reported findings that differentiated the combat and the jungle boots from one or more of the commercial items and that have implications for development of future generations of military footwear. Some of the findings were related to differences among footwear items for the vertical ground reaction force component.

During marching, use of the combat and the jungle boots resulted in the highest impact peak forces. The military boots were also associated with high impact forces during the jump/landings. During walking and marching, the magnitudes of second maximum vertical force, the thrust or propulsive peak, were relatively large for the combat and the jungle boots, especially when compared with the magnitudes for the Reebok Pump and the Nike cross trainer. These results, along with the high values of peak g for the military boots obtained by Hamill and Bensel (1992) on the impact test, suggested that means to improve shock attenuation in both the heel and the forefoot areas be addressed in design of future military footwear.

Unlike the results for walking, marching, and the jump/landings, the magnitudes of the vertical ground reaction force peaks during running were either essentially the same for all footwear types or were lower for the military boots than for some of the commercial items. Furthermore, there was no evidence during running of differences among footwear types in the extent of maximum knee flexion, a kinematic adjustment that Clarke, Frederick, and Cooper (1983) reported in association with differences in shoe midsole hardness. In addition, the military boots resulted in relatively small rearfoot angles at foot strike during running, whereas Nigg et al. (1987) found larger rearfoot angles at foot strike with harder midsole material and maintained that this adjustment served as a protective mechanism for controlling application of external ground reaction forces to the foot.

In light of the high vertical ground reaction forces for the military boots during walking, marching, and the jump/landings, and the lack of evidence of kinematic adjustments at foot strike during running in the military boots, Hamill and Bensel (1996a, 1996b) suggested that, during running with the military boots, the vertical ground reaction forces may have been transmitted to the skeletal system essentially unattenuated. This possibility further emphasized that improved shock attenuation should be addressed in future military footwear. In addition, the men's fastest times to first maximum force during running occurred with the combat and the jungle boots and the women's fastest times occurred with the combat boot. This finding was compatible with the materials testing in which Hamill and Bensel (1992) found that the shortest times to peak g on the impact test were associated with the military boots.

In analyzing sagittal plane kinematics during the locomotor movements, Hamill and Bensel (1996a, 1996b) also found differences among the footwear items. These were related to metatarsal angle measurements. During walking, marching, and running, use of the military boots and the Red Wing work boot resulted in the greatest degrees of metatarsal flexion, whereas use of the Reebok Pump generally yielded the lowest values for metatarsal flexion. The flexion velocities for the combat boot and the jungle boots were also quite high. The results for the military boots describe an extreme and rapid raising of the heel by movement about the metatarsal-phalangeal joints. Hamill and Bensel maintained that this action, performed in a repetitive manner during locomotion, could strain the long plantar ligaments extending from the heel to the ball of the foot, precipitating the onset of plantar fasciitis.

In measuring forefoot flexibility during the materials testing phase of this research, Hamill and Bensel (1992) found the Red Wing work boot to be the least flexible of the items tested, followed by the combat and the jungle boots, with the Reebok Pump being very flexible. Hamill and Bensel (1996a, 1996b) proposed that, because of stiffness of the forefoot, the military boots and the Red Wing work boot required a relatively great degree of metatarsal flexion to accomplish toe-off and propel the body forward into the next step. This finding suggested that means to improve forefoot flexibility be addressed in design of future military footwear.

Results from the human user testing pertaining to rearfoot motion parameters also had implications for development of future military boots. In those instances in which footwear had a significant effect on rearfoot angles during ground contact, the military boots tended to be associated with the smaller angles, indicating less movement of the calcaneus relative to the lower leg, than some of the other footwear types tested. This was the case in the male and the female data for rearfoot angle at foot strike during running, as well as total rearfoot motion during running (Hamill and Bensel, 1996a, 1996b). Furthermore, in assessing rearfoot stability during the materials testing phase of this research, Hamill and Bensel (1992) found the combat and the jungle boots to be highly stable at both the medial and the lateral borders of the heel.

Excessive subtalar joint pronation has been linked to lower extremity injury (Hlavac, 1977; James et al., 1978). However, pronation is a mechanism for decreasing the forces transmitted to the body following foot strike (Clarke, Frederick, and Hamill, 1983; Nigg et al., 1986). Thus, Hamill and Bensel (1996a, 1996b) suggested that, in design of future military footwear, no action be taken that would increase rearfoot stability. They also maintained that design changes that may indirectly result in somewhat decreased rearfoot stability, such as selection of softer midsole materials (Clarke, Frederick, and Cooper, 1983), would not be likely to compromise the stability of the military boots.

Some of the results of the human user testing also had implications for another aspect of future military boots, the design of the upper. All of the footwear tested extended to at least the level of the lateral malleolus, but there was a difference of almost 14 cm between the item with the highest upper, the combat boot, and the item with the lowest upper, the Nike cross trainer. After the combat boot, the jungle boot, followed by the Red Wing work boot, had the highest upper. The longest times to complete the agility course run were recorded with these three footwear items (Hamill and Bensel, 1996a, 1996b). The course demanded rapid changes in direction and in pace. Hamill and Bensel proposed that the high uppers restricted ankle motion, thereby increasing course completion times.

Hamill and Bensel (1996a, 1996b) reported that analyses of sagittal plane kinematics during walking, marching, and running provided evidence that the military boots and the Red Wing work boot restricted ankle movement to a greater extent than the other footwear tested. The ankle angle data collected during the locomotor movements revealed that the smallest maximum dorsiflexion angles and the greatest negative magnitudes of dorsiflexion velocity were generally associated with the military boots and the Red Wing work boot, the three footwear types having the highest uppers.

According to Hamill and Bensel (1996a, 1996b), the ankle angle data recorded during the jump/landings also revealed that use of the military boots and the Red Wing work boot generally resulted the smallest maximum dorsiflexion angles. However, the lowest dorsiflexion velocities were achieved with these footwear items. In a study of sagittal plane kinematics during jump/landings, McNitt-Gray (1991) found that the ankle joint, as well as the hip and knee joints, was in an extended position at touchdown. McNitt-Gray maintained that this posture provides the potential for the full range of joint motion to be used to minimize the load imposed on the skeletal system during landing. Hamill and Bensel, therefore, proposed that the participants in the human user testing may have been exposed to more substantial loads on the body during jumping in the military boots and the Red Wing work boot because of constrained ankle movement. They also maintained that limited dorsiflexion may have resulted in greater loads being transmitted to the body during walking, marching, and running in the military boots and the Red Wing work boot. Hamill and Bensel concluded that these findings, together with the longer times on the agility course when these footwear items were used, suggest that efforts addressing future military footwear consider whether the upper heights of the present boots are optimal in terms of ankle mobility and protection of the musculoskeletal system from impact loads.

RECOMMENDATIONS FOR FUTURE MILITARY BOOTS

Footwear must perform a number of functions. James et al. (1978) suggested that footwear must attenuate impact shock and control the medio-lateral motion of the foot during contact with the ground. These, however, are only two of the functions of footwear. In addition, footwear must provide protection and enhance, or at least not hinder, the performance of the wearer. Confounding these issues is the fact that footwear must be utilized for a multitude of activities, and a given footwear design may not be the most appropriate for every one of these activities. For example, a shoe that functions well for running may not be particularly good for walking or for landing from a jump. Furthermore, a running shoe may function well only on certain terrains or in distance running, but not sprinting.

In the athletic shoe industry, manufacturers have not addressed the issue of producing a single footwear design for a multitude of applications. Instead, they have created specific shoes for specific purposes. There are shoes designed for running, others for walking, others for tennis, and the like. In fact, among running shoes, some are structured for distance running, whereas others are structured for sprinting and yet others for cross-country.

Unlike athletic shoes for the civilian market, a single design of military footwear must be used for a wide range of activities. The weight and bulk of a number of pairs of shoes cannot be added to the loads that soldiers carry nor can soldiers stop to change shoes as activities, surfaces, and terrains change. It is likely therefore that, depending upon the activities being performed and the situations being encountered, the present military boots sometimes enhance and sometimes degrade the performance of the wearer, sometimes protect the wearer from injury and sometimes make the wearer more vulnerable to injury. In considering the next generation of military footwear, again the design of the "perfect" boot does not seem a practical possibility. What can be done, however, is to structure a boot that is a series of compromises with the best of all worlds represented. The goal would be a boot that, although not 100% satisfactory in every situation, is above average in acceptability in most of them.

The remainder of this section deals with specific recommendations for future military footwear, based on the findings from the materials testing (Hamill and Bensel, 1992) and the human user testing (Hamill and Bensel, 1996a, 1996b) of present military boots and commercial sport and work shoes. The recommendations apply primarily to a new boot that would serve the same functions as today's combat boot. That is, a boot to be used mainly in temperate environments by ground troops. The recommendations also apply to a new jungle boot, although consideration of characteristics desirable in footwear to be worn in hot-wet environments is beyond the scope of this report. The principal issues addressed in the recommendations are: 1) shock attenuation; 2) midsole stiffness; 3) medio-lateral stability; and 4) upper design.

Shock Attenuation

During each ground contact, a load is placed on the human body. The load is the sum of body weight and the weight of any additional external items being worn or carried. Even in the absence of an external load, the vertical ground reaction force at impact ranges from 1.2 times body weight during walking (Hamill, Bates, and Knutzen, 1984) to 2 to 3 times body weight during running (Cavanagh and Lafortune, 1980). In landing from a jump, the vertical ground reaction force at impact can be as great as 6 to 10 times body weight, depending upon the height of the drop (McNitt-Gray, 1991). Whatever the load, the individual must attenuate this shock during the impact phase of ground contact.

Individuals have three methods of reducing the magnitude of the shock to which the system is exposed: 1) Change the surface on which they are acting; 2) Change their body kinematics; and 3) Change their footwear. In terms of the surface, a softer, more compliant surface will result in less shock to the system. However, selecting a good surface is not always a reasonable alternative, particularly for soldiers in military operations, where mission requirements dictate the surfaces on which they act. The second method, altering the kinematics, or body movement patterns, is also not a reasonable choice because an altered movement pattern may itself lead to injury. For example, increasing the knee flexion angle in response to an increased load on the body causes muscle soreness within 72 hours of the exercise (Hamill, Freedson, Clarkson, and Braun, 1991). Therefore, it would be desirable to maintain the normal body kinematics regardless of the load.

The third method of reducing the shock, changing the footwear, is probably the most effective intervention in the case of soldiers. The footwear platform, comprised of the insert and the midsole, is the functional unit of the footwear responsible for shock attenuation. This unit can be adjusted to better attenuate the shock of impact.

In Phase II of the research conducted by Hamill and Bensel (1996a, 1996b), women were tested while wearing lightweight clothing and while wearing the clothing plus load-carrying gear totalling 50 lb. Men were tested under these two conditions and under an additional condition in which the load-carrying gear totalled 70 lb. It was found that the magnitude of the ground reaction forces increased as the weight of the load increased. However, the participants revealed slight, non-significant alterations in the degree of knee flexion with increases in the load. Furthermore, there was little additional activity in the muscle groups of the leg as load was increased.

With regard to the footwear variable, the Phase II testing revealed few changes in hip and knee angles as a function of footwear type (Hamill and Bensel, 1996a, 1996b), in spite of the fact that physical testing had revealed extensive differences among the footwear items in terms of shock absorbency and flexibility (Hamill and Bensel, 1992).

The implication of the findings with regard to both load weight and footwear effects is that the shocks of ground contact were not attenuated to any great extent by the participants. Thus, the loading forces acted on the lower extremity joints relatively unattenuated. It would be appropriate, therefore, to structure future boots differently than today's boots are in order to better attenuate the shocks of ground contact.

Insert

The insert in the combat and the jungle boots tested by Hamill and Bensel (1992, 1996a, 1996b) was made of a closed-cell, urethane foam (Poron®) with a fiberboard backing. The insert provided little shock-absorbing capability compared with other inserts used in the footwear tested (Hamill and Bensel, 1992). In addition, the Poron insert was flat to the surface of the leather insole, so it did not contribute to conformance of the foot to the footwear platform.

Foti, Derrick, and Hamill (1992), using an in-shoe pressure measurement system, found that a firm and a soft insert material did not differ in shock attenuation. However, the firm material resulted in a point application of force on the foot, whereas, with the soft material, force was distributed more evenly over the plantar surface of the foot. Thus, the soft material was more comfortable than the firm even though the total force on the body was the same.

In order to achieve improved shock absorbency, or at least better distribution of forces over the plantar surface of the foot, it is recommended that an insert comparable to that used in the Rockport hiking boot be used in military boots. The insert in the Rockport boot consists of a sockliner material on top of a contoured foam base. The foam is an ethyl vinyl acetate with a durometer of approximately 35. This foam is inadequate for military use because it deteriorates rapidly. However, a polyurethane foam of a similar durometer could easily be substituted. Contouring of the insert should prevent the foot from sliding inside the boot and, thereby, aid in prevention of friction blistering on the plantar surface of the foot.

Midsole Construction

An even more important change for military boots than the replacement of the insert is a change in construction. The combat and the jungle boots do not have a midsole, per se. Rather there is a combined outsole and midsole, which is direct-molded to a leather insole. The outsole/midsole is a single density, one piece, hard rubber structure with a steel shank.

During locomotion, it is typically the rearfoot that is exposed to the impact forces associated with foot strike (Cavanagh and Lafortune, 1980). Impact forces are generally lower in magnitude than the propulsive forces to which the forefoot is exposed, but have a much steeper rise time. In landing from a jump, on the other hand, the forefoot is exposed to the impact forces of foot strike, which are lower than the forces to which the rearfoot is exposed, but again have a steeper rise time (McNitt-Gray, 1991). A single density midsole cannot respond to these different loading situations.

In the impact testing conducted during Phase I, the combat and the jungle boots evidenced substantially higher peak g values and shorter times to peak g than all the commercial items included in the research except the Red Wing work boot (Hamill and Bensel, 1992). This was the case in the testing of both the heel and the forefoot regions of the footwear. In Phase II, the military boots yielded higher impact forces than the commercial footwear during marching and the jump/landings. During running, on the other hand, impact peaks for the military boots were equal to or lower than those for some of the commercial items. Furthermore, during running, there was no evidence of differences among footwear types in the extent of maximum knee flexion or lower extremity muscle activity (Hamill and Bensel, 1996a, 1996b). Thus, impact forces associated with the military boots were most likely transmitted to the wearer's skeletal structure. If, as the Phase I and the Phase II testing would indicate, the structure of the soles of the military boots is indeed too firm, it is likely that repetitive loading associated with locomotion and other physical activities will result in injury to the wearer.

In the commercial arena, the midsole has probably been the most studied area in footwear biomechanics. There are a number of midsole structures that have been shown to provide good shock absorbing characteristics and could be considered for incorporation into military footwear. Essentially, the military boots should have a multi-component, multi-durometer midsole.

In its simplest form, the rearfoot, or heel area, would be a three-layer, sandwich structure having a firm, protective outsole made of rubber. The proposed construction is illustrated in Figure 1. Outsole materials and outsole tread designs could be identical to those presently used in the combat and the jungle boots. The layer next to the outsole, the first of the midsole layers, would be constructed of a closed-cell, foam polymer that is less rigid and a better shock absorber than the outsole material. Candidate materials are polyurethane or hytrel foam. The layer on top of this, that is, the second layer of the midsole, would be a material similar in structure, but less dense, thus providing more shock attenuation. The midsole layer closest to the foot, the heel lift, would be made of a rubber that is softer than the rubber used in the outsole.

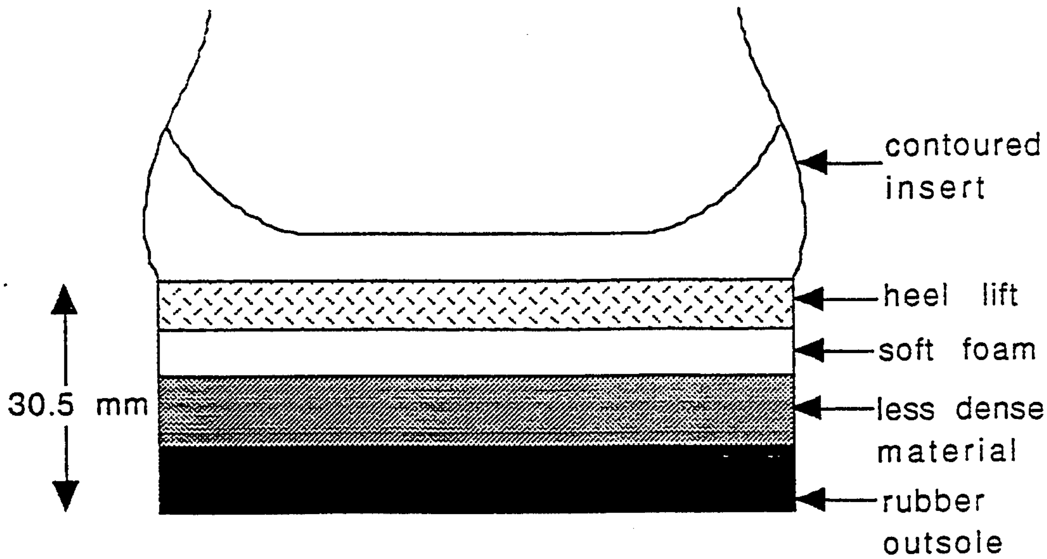

Figure 1. Rear view of proposed heel construction for increased shock absorption, including a contoured insert.

Determination of the exact vertical dimensions and densities of the layers comprising the midsole requires further testing and evaluation. However, given the materials available to select from, it should be possible to form a multi-density midsole without compromising the medio-lateral stability of the boots.

There are a variety of midsole constructions used commercially that employ a layered approach. In some commercial footwear, the layered approach is taken one step further with the medial and the lateral portions of a layer being differentiated. That is, the medial aspect of two of the three midsole layers is much firmer than the lateral aspect. This construction takes into account the normal footfall pattern during locomotor activities. For most individuals, first contact of the foot with the ground occurs at the lateral portion of the heel (Cavanagh and Lafortune, 1980). Thus, the purpose of the softer lateral side of the midsole is to aid in attenuating the impact shock at foot strike. As the foot accommodates to the surface by rolling medially, the firmer construction of the medial aspect of the midsole controls the degree of rearfoot motion. Construction of a midsole with materials of different densities comprising a single layer is illustrated in Figure 2.

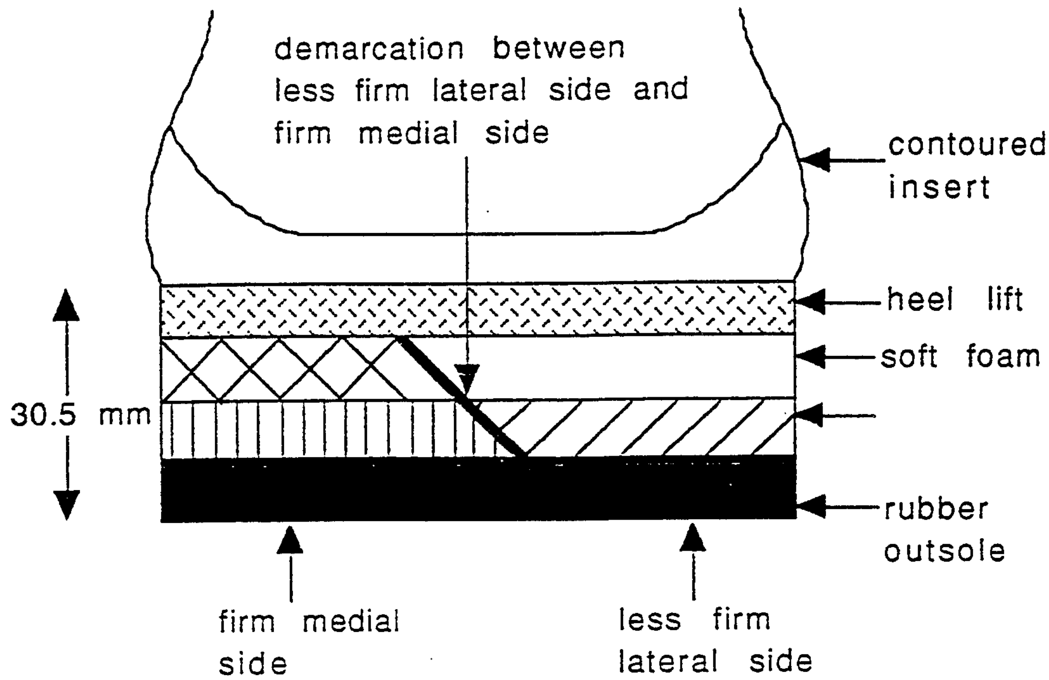

Figure 2. Right foot rear view of proposed heel construction for increased shock absorption, including a contoured insert.

A major problem in implementing the construction presented in Figure 2 in military boots lies in the range of activities, terrains, surfaces, and the like to which the boots are exposed. With considerable testing, it may be possible to identify materials and distributions of densities for each midsole layer that are appropriate for some situations soldiers encounter. However, it is unlikely that the midsole would function well in most situations. It terms of cost of implementation and benefit to the user, the midsole construction illustrated in Figure 1 is the better alternative and is the one recommended for future military boots.

As mentioned previously, shock attenuation is critical not only in the heel, which is exposed to impact forces during locomotion, but in the forefoot region as well. The loads to which the forefoot is exposed during locomotion are of greater magnitude than those at the heel, but the loads at the forefoot increase over a longer period of time (Cavanagh and Lafortune, 1980). Thus, a good foam insert at the forefoot of a shoe is generally sufficient for shock attenuation. There are situations, however, in which the forefoot is exposed to impact forces. Landing from a jump is an example of such a situation (McNitt-Gray, 1991). In landing, an individual typically displays plantarflexion at the ankle (i.e., points the toes toward the ground) in order to insure that impact occurs in the region of the metatarsal heads on the plantar surface of the foot. Thus, multifunction footwear, such as military boots, should provide for attenuation of impact forces to the forefoot.

In their impact testing of military and commercial footwear, Hamill and Bensel (1992) found that peak g values at the forefoot region of the combat and the jungle boots were exceptionally high. The peak g values were roughly 33% to over 100% higher than those obtained in the testing of such commercial footwear as the Nike cross trainer and the Reebok Pump, shoes specifically constructed to provide forefoot cushioning. In the human user testing, Hamill and Bensel (1996a, 1996b) found that vertical ground reaction forces during the jump/landings were greater in the military boots than in the Reebok Pump and the Nike cross trainer.

The test findings indicate that there is a need to improve the forefoot cushioning in military footwear. However, there is a problem in doing so because the forefoot profile of the present boots offers little allowance for inserting a midsole construction similar to that recommended for the rearfoot. The thickness of the forefoot in a size 9 combat boot is only 8 mm. Thus, insertion of a multilayer midsole may compromise the integrity of the protective outsole. This problem is not unique to military footwear. Footwear manufacturers have the same difficulty keeping a low forefoot profile while providing maximum shock absorption in basketball shoes.

Few manufacturers of commercial footwear are truly successful in attenuating impact forces in the forefoot by use of midsole systems. Thus, many manufacturers alter the insole or insert in the forefoot area. Several companies use a forefoot pad beneath the insert that is shaped to cover the heads of all the metatarsals on the plantar surface of the foot, the primary point of landing from a jump. The material used most often is sorbothane. This material has excellent shock absorbing properties, attenuating the impact forces and lengthening their rise time. There are materials other than sorbothane that serve the same function. These include uncured polyurethanes and silicon gels.

It is recommended that a forefoot pad be used in military boots for shock absorbency. There are two other approaches that should be considered and may prove feasible. One is the addition of a single layer of soft foam over the outsole in the forefoot region. The other is the "no-heel" design illustrated in Figure 3. This design allows for maximum layering, a thicker forefoot support, and a variable stiffness, full-length shank or, in the case of the jungle boot, a protective plate. A variant of the outsole portion of the construction illustrated in Figure 3 is commonly worn by Army personnel serving as crews on tanks and other combat vehicles in order to avoid the hazard of catching the heel on the exterior surfaces of the vehicles.

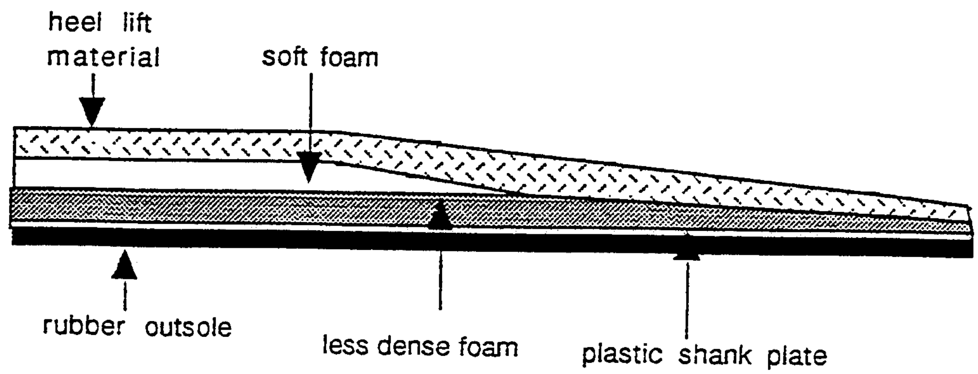

Figure 3. Proposed flat midsole design incorporating a multi-layer midsole and a plastic support/protective plate.

The outsole tread patterns and materials of the present combat and jungle boots are compatible with the midsole structure presented in Figure 3. The hard rubber of the current boots could be used to form the outsole of the no-heel boot.

Midsole Stiffness

Midsole stiffness refers to the amount of effort that the individual must use to flex a shoe in the forefoot region. The higher the stiffness value, the greater the force the individual must exert to bend the shoe as the body pivots over the base of support. Cavanagh (1980) suggested that the less flexible the shoe, the more the lower extremity muscles must be stressed. Conversely, a more flexible shoe requires less muscular effort to bend. It is intuitive that soldiers should not be fatigued by their equipment, especially their footwear.

In the physical testing conducted by Hamill and Bensel (1992), the combat and the jungle boots had relatively high stiffness values, as did the Red Wing work boot. These less flexible footwear types had a single-density, one-piece, combined outsole and midsole with a steel shank and, in the case of the jungle boot, a steel plate, as well. The footwear types with relatively low stiffness values, the Nike Air Max and the Reebok Pump, had separate outsoles and midsoles, comprised of materials differing in density, and did not have steel shanks or plates.

A firm, single-density outsole/midsole cannot accommodate well to forefoot flexion. During flexion, the outer surface of the material is undergoing tension, while the surface closest to the foot is undergoing compression. With a firm, single-density material, the outer surface resists stretching and, therefore, does not easily accommodate to bending. The steel shanks in the military boots and in the Red Wing work boot extend from the heel forward, terminating just short of the flex region; the steel plate in the jungle boot extends the full length of the shoe. Both the shank and the plate appear to contribute to stiffening the sole and further increasing its resistance to stretching.

There are several approaches that may be taken to increase the flexibility of military boots. One is the use of a multi-layered midsole in the forefoot region, as described previously. If the layers are structured such that the materials comprising them decrease in density from the outsole toward the foot, the boots should show increased flexibility relative to today's items. The softer materials close to the foot will compress more easily; the firm outsole will be thinner and, thus, less resistant to tension.

The steel shank in the combat and the jungle boots supports the arch area of the sole. The steel plate in the jungle boot protects the plantar surface of the foot from puncture by spikes and other penetrating objects. Although removal of the shank and the steel plate would certainly increase the flexibility of the forefoot, this is not a feasible alternative. Rather, it is recommended that alternate materials serving the same purposes be considered for application in future boots.

The steel shank now in the military boots is uniform in stiffness. A material other than steel, such as a carbon fiber or a hard plastic, could be tailored so that stiffness of the shank decreases along its length. The shank would be stiffest at the heel and most flexible toward the forefoot. This change should decrease the localized pressure caused by the shank just behind the metatarsal heads, allowing the outsole rubber material to stretch. The total effect should be an increase in the flexibility of the forefoot.

The approach suggested to improve the flexibility of the shank could not be applied to the steel plate in the jungle boot because the protective plate runs the length of the boot. Some benefit may be gained by replacing the steel with a hard plastic, provided the required protective properties are not compromised. Regardless of the material, replacing the flat plate with a corrugated one could improve forefoot flexibility. This concept is illustrated in Figure 4.

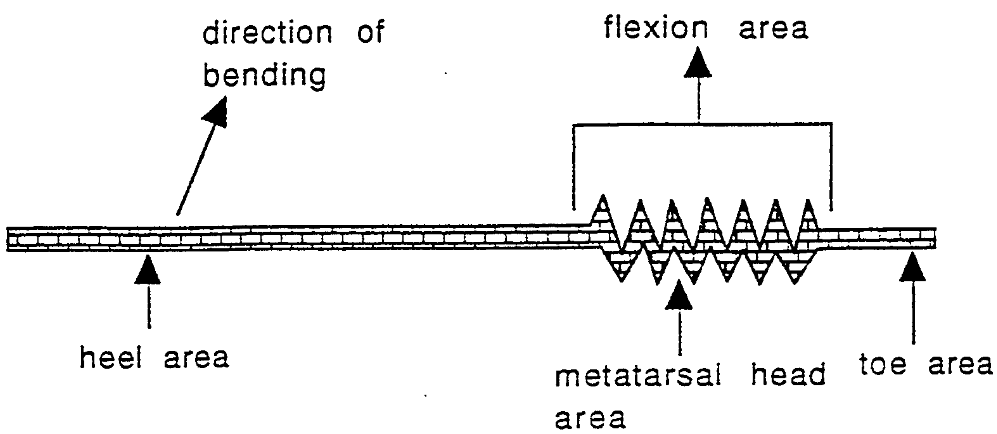

Figure 4. Steel/plastic protective plate design to enhance forefoot flexibility.

Medio-lateral Stability

Medio-lateral stability refers to the side-to-side control that the footwear provides the foot during the initial portion of ground contact. Generally, it refers to control of the action at the subtalar joint. In locomotor activities, the foot strikes the ground on the lateral aspect of the heel and proceeds to roll medially and then antero-posteriorly until it is flat on the locomotor surface (Clarke et al., 1984). It is in this manner that the foot adapts to the surface. Medio-lateral control is reflected in the magnitude of rearfoot motion.

The amount of rearfoot motion is determined in large measure by the footwear being worn, with a firmer midsole being more stable and permitting less movement (Clarke, Frederick, and Hamill, 1983). In both physical testing and human user testing, Hamill and Bensel (1992, 1996a, 1996b) found that the medio-lateral stability of the combat and the jungle boots was more than satisfactory. Therefore, no design changes are recommended for future military boots that would alter this positive feature. However, extreme stability may compromise the shock attenuating capabilities of the footwear; as stability increases, shock attenuation decreases, and vice versa (Clarke, Frederick, and Cooper, 1983).

It was recommended previously that the shock attenuation characteristics of military boots be improved in future generations of this footwear. If this were done, it would follow that the new boots would not be as stable as today's boots. However, it is unlikely that the midsole construction proposed would result in a substantial degradation of stability relative to that in the present, highly stable boots.

Upper Construction

The upper of a boot or shoe is comprised of those components of the footwear that are above the midsole, exclusive of the insert. For purposes of this discussion, a distinction must be made between low quarter, or low cut, uppers, which are commonly found in dress shoes and sport shoes manufactured for the general civilian market, and high top uppers found in military boots, some work boots, and some special-purpose sport shoes. In low quarter footwear, construction of the upper has little effect on functioning of the foot and leg other than keeping the foot centered on the midsole and protecting the foot from extraneous trauma. In high top boots, on the other hand, the upper is also designed to stabilize the ankle and to protect the lower leg from extraneous hazards, such as brush and thorns.

The element of the uppers of the military and the commercial boots tested by Hamill and Bensel (1992, 1996a, 1996b) that is noteworthy is the height. Specifically, the fact that the combat and the jungle boots extend farther up the leg than the civilian boots. For example, the military boots are 2 cm higher than the Red Wing work boot in a comparable size. In a size 9, the military boots extend approximately 7 cm above the malleoli. The high upper of the military boots does not present a problem during forward locomotion. In fact, the upper may have a positive effect because it stabilizes the ankle. However, there are situations in which the height may be deleterious. Landing from a jump and rapidly changing direction are two of the situations.

In landing from a jump, the foot is plantarflexed at the ankle so that initial contact between the foot and the landing surface is made in the area of the metatarsal heads. The larger the plantarflexion angle at touchdown, the greater the angular displacement over which the impact force acts as the ankle dorsiflexes and the foot returns to a neutral position after touchdown (McNitt-Gray, 1991). Thus, plantarflexion serves as a shock-attenuating mechanism.

One reason for the high upper of the combat and the jungle boots is that this footwear is used by airborne personnel for parachute drops, where the risk of ankle fractures and sprains is relatively high (Murray-Leslie, Lintott, and Wright, 1977). The concept is that a boot with a high upper will stabilize the ankle, thereby aiding in prevention of ankle injuries associated with landing. Although they may well stabilize the ankle, the military boots and similar footwear tie the foot and the leg together. This is attributable to the fact that the upper is one piece, extends above the malleoli, and conforms closely to the leg. The result is that movement of the foot in the sagittal plane is restricted. Thus, in landing from jumps, an individual cannot take full advantage of the shock attenuation afforded by a large plantarflexion angle.

In the analysis of men and women performing jump landings from 0.32 m and 0.72 m, Hamill and Bensel (1996a, 1996b) found evidence of the restricted movement associated with high uppers. Their data revealed that the military boots and the Red Wing work boots, the items with the highest uppers, had lower values for maximum dorsiflexion angle following touchdown than the other footwear types tested. The implication for military boots is that an approach for stabilizing the ankle without tieing the foot and the leg together, thereby limiting plantarflexion, would benefit airborne personnel when landing from a parachute drop, and other personnel when jumping from heights.

As was mentioned, changing direction rapidly, like landing from a jump, is another situation in which a high upper may not be advantageous. Footwear with a high upper stabilizes the ankle much like a prophylactic ankle brace does. When the ankle joint is stabilized in this manner, the joint is less mobile. However, the foot-ankle complex must be mobile in order for an individual to change direction rapidly. Hamill and Bensel (1996a, 1996b) tested men and women on an agility course that required a number of directional changes. They found a trend toward increasing times to course completion with increasing heights of the uppers of the footwear being worn. The implication for military boots is that a lower cut upper would improve the efficiency of soldiers' movements in situations in which rapid directional changes are required.

It is recommended that the upper height of future military boots be decreased compared with the heights of present boots so that the upper extends approximately 2 cm above the malleoli. This height should minimize interference with foot-leg motion and provide some protection from extraneous hazards to the foot and lower leg. For activities in which a high level of ankle stability is needed, as may be the case in parachute landings, additional ankle support should be provided in the form of a prophylactic ankle brace. The brace used should be one that does not tie the foot and the leg together. Rather, it should allow independent action of these segments.

SUMMARY OF RECOMMENDATIONS

The following recommendations are made for designing of next-generation military boots:

1. Some of the new "high-tech" materials, such as hytrel foms, carbon fibers, and plastics should be used in boot construction.

2. To improve shock attenuation, the boots should have a removable insert consisting of a sockliner material on top of a contoured, foam base.

3. The boots should have a separate outsole and midsole. To aid in shock attenuation, the midsole should be multi-layered with materials differing in density comprising the layers.

4. The present combat and jungle boots have good medio-lateral stability. This positive feature should be retained in the next-generation boots.

5. A material other than steel, such as a hard plastic or a carbon fiber, should be used for the boot shank. The shank material should be tailored so that it is stiffest at the heel and most flexible toward the forefoot.

6. The boot upper should extend to approximately 2 cm above the level of the malleoli. This height should permit independent foot-leg motion, while stabilizing the ankle.

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