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Biomechanical Properties of Infantry Combat Boot Development

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SUMMARY

Problem.
One of the most important items of U.S. Marine Corps standard military issue is the combat boot. Military requirements demand a boot that is comfortable, durable, and enhances the locomotor capabilities of the soldier. Research on military personnel has demonstrated that an early onset of muscular pain and fatigue occurs while wearing rigid boots during excessive movement and activity. At Marine Corps Recruit Depot (MCRD), San Diego, 40% of all recruits going through "boot camp" report to sports medicine or podiatry with musculoskeletal complaints. These conditions have a significant impact, resulting in 53,000 lost training days and a cost of $16 million per year. Since the anatomical sites of most of these training-related complaints are below the knee, a further look into the role of footwear in the development of musculoskeletal injuries was warranted.

Objective.
The objective of this research was to evaluate the biomechanical properties of current commercially available boots and to provide a recommendation for a combat boot with optimal biomechanical properties.

Approach.
The evaluation included objective physical tests of the cushioning and material characteristics of military and commercial footwear, and biomechanical tests to evaluate the human subjective biomechanical performance of the footwear. At the conclusion of the biomechanical tests, a brief survey addressing comfort parameters was administered to each subject.

Results.
Data derived from the boot impact tests revealed that all of the commercially available boots tested superior to the standard-issue jungle and leather combat boots. According to the subject performance tests, the greatest shock absorption and lowest power requirements were obtained with the Asolo 540 boot, the Bates Lite 924 boot, and the polyurethane prototype boot. The greatest stability was achieved with the Danner Acadia boot, the leather combat boot, and the Bates Lite boot. The jungle boot improved markedly in each of the subject test parameters with the addition of the polyurethane sole (polyurethane prototype boot).

Conclusion.
Our findings suggest that currently available boots offer superior features over the standard-issue military boots. This study illustrates that several optimal characteristics from various commercially available boots can be combined to create a military prototype boot which surpasses that which is currently in use.

One of the most important pieces of U.S. Marine Corps standard military issue is the combat boot, which is used in training, garrison, and field environments. Military requirements demand a boot that is comfortable, durable, and enhances the locomotor capabilities of the soldier (Hamill & Bensel, 1996). In the 1980s, the latest version of the combat boot was developed at the U.S. Army Natick Research, Development and Engineering Center. This boot has a leather upper, rubber outsole/midsole, and a removable urethane foam insert. All U.S. Marine Corps recruits receive the combat boot during processing at "boot camp." Another footwear item, the "jungle boot," is issued for use in hot, humid conditions, but it may be worn in other environments.

Current boot designs involve thick-soled, rigid uppers that restrict natural gait patterns during physical activity. The designs of military boots predominantly have conformed to the average foot dimensions of the American soldier, thereby reducing the inventory of sizes and widths, and providing the ideal midsole for military purposes (Potter, 1961). Research on military personnel has demonstrated that an early onset of muscular pain and fatigue occurs while wearing rigid boots during excessive movement and activity (Lake, 1952). Bensel (1976) investigated whether use of the tropical combat boot or leather combat boot would significantly reduce the number of cases of lower extremity disorders during training. In that study, approximately 900 Marine recruits, wearing either style of boot, were monitored over a 12-week training period. It was concluded that the number of cases of heel contusions, toe paresthesia, and retro-calcaneal bursitis were significantly increased in the recruits wearing tropical boots. Bensel also concluded that only new testing concepts rather than further manipulation of boot design at the expense of the soldier would facilitate improved footwear.

At Marine Corps Recruit Depot (MCRD), San Diego, 40% of all recruits going through boot camp report to sports medicine or podiatry with musculoskeletal complaints during their training (Shaffer, Brodine, Corwin, Almeida, & Maxwell Williams, 1992). These conditions have a significant impact, resulting in 53,000 lost training days and a cost of $16 million per year (Naval Health Research Center, 1993). Since the anatomical sites of most of these training-related complaints are below the knee, a further look into the role of footwear in the occurrence of musculoskeletal injuries was warranted.

One of the biomechanical risk factors for a musculoskeletal injury is impact shock. Shock waves are generated by repeated impact between the foot and the ground. These shock waves are thought to be associated with many different kinds of musculoskeletal injuries (James, Bates, & Osternig, 1978). Laboratory testing has shown a wide variation in impact-loading between different combat boots, with or without added shock-absorbing insoles (deMoya, 1982; Hamill & Bensel, 1992, 1996). The design of footwear for running should depend on a sound knowledge of the force and pressure environment during ground contact since footwear is the major means of attenuating the impacts the body experiences during running (Cavanagh & LaFortune, 1980).

The goal of this study was to evaluate the biomechanical aspects of current commercially available boots and stock system boots and to provide a recommendation for an improved design for a combat boot. The evaluation included objective physical tests of the cushioning and material characteristics, and biomechanical tests to evaluate the human subjective biomechanical performance. Physical testing was performed on the leather combat boot, the jungle boot, and a panel of commercial boots. Data from the physical tests were used to create prototype boots with standard jungle boot uppers and revised soles with optimum shock absorption. This research was specifically tasked with addressing the shock absorption and cushioning characteristics of the boots. Other parameters, such as waterproofing and lacing systems, are beyond the scope of this report.

Methods

This study tested existing Marine Corps leather and jungle boots for baseline performance characteristics and compared them with current commercially available boots. The commercial boots were pre-selected by the United States Marine Corps for authorized optional wear with uniform. The biomechanical measurements fell into two categories: (a) physical tests aimed at mechanically characterizing the entire boot or the boot's component materials, and (b) tests using human subjects to quantify various physical properties and the body's response to wearing boots. The human biomechanical tests were selected on the basis of existing data correlating specific biomechanical characteristics and likelihood for musculoskeletal overuse injury. Biomechanical testing was also performed on a high-performance running shoe and 2 prototype boots designed from the results of the physical testing.

Physical Tests

Materials. The impact tests were performed using 8 different current commercially available boots, as well as a pair of standard-issue jungle boots and a pair of leather combat boots, for a total of 10 boot designs. The commercially available boots tested were the Rocky RB7774, Red Wings 04473-2, Timberland Iditarod, Hi-Tec Magnum, Browning Climber 400, Danner Acadia, Bates Lite 924, and Northlake N9013. All boots were prepared for testing by separating the sole from the rest of the boot and removing the insoles.

Equipment. A computerized, gravity-driven impact tester, the Exeter Impact System, was used to provide force deformation data on the footwear materials. This device drops an 8.5-kg weighted shaft a distance of 50 cm on to the surface of the shoe. The total impact force with no resistance is 42.5 peak *g*. The shaft was instrumented to provide a recording of displacement and force. This device was designed to recreate the impact-loading condition experienced by runners at heel strike.

Data collection. Data were gathered while each boot was impacted 10 times separately on the heel and forefoot. Impact data were used to quantify the amount of energy absorbed. Variables measured included material thickness, peak *g*, time to peak *g*, peak force, percentage penetration, and percentage energy return. Definitions of the variables measured for the physical tests are provided in Appendix A. The material tests selected were based on American Society of Testing and Materials (ASTM) standards.

Subject Performance Tests

Subjects. Ten male U.S. Marine Corps volunteers served as subjects. Age range of the subjects was 25 to 41 years, with a mean age of 31 years. Prior to testing, all subjects were screened for any lower extremity disorders using a brief physical exam and a medical history questionnaire.

Materials. All subjects were tested using 9 different footwear designs as follows: a standard military combat boot, a military hot-weather (jungle) boot, the Danner Acadia boot, the Bates Lite 924 boot, the Asolo 540 hiking boot, the Northlake N90313 boot. Two prototype boots with jungle boot uppers were developed using the information from the boot impact tests. Both prototype boots had quarter-inch polyurethane insoles, and polyurethane midsoles. However, one boot had a polyurethane outsole, while the other boot had a rubber (Vibram) outsole. An Asics Gel 125 shoe was also included for comparison as a high performance running shoe. The subjects were also tested while running barefoot.

Equipment. The ground reaction force was measured with a piezoelectric force plate housed in a commercially manufactured treadmill. Rearfoot angles were measured by attaching a flexible goniometer to the rearfoot of each subject. A spring-mass biomechanical model was created to analyze the ground reaction force data. The model calculated the peak impulse-loading and power absorption of the subject while wearing each of the test footwear and while barefoot.

Data collection. Various physical measurements were obtained from each subject. Physical measurements included weight, height, and shoe size. Bilateral physical measurements included ankle circumference (over malleoli and above malleoli), lower leg circumference (9 inches boot height), arch height, lateral malleolus height, knee joint line height, greater trochanter height, arch length, toe length, and foot width.

Ground reaction force data and rearfoot motion were collected while the subjects ran at 8 mph and 0% grade on a motor-driven treadmill. The force platform provided data on vertical force and center of pressure. Ground reaction forces were normalized against the body weight of the subject in the gait cycle to minimize anthropometric variations and to develop a reference standard. The force plate determined when foot contact and toe-off occurred. From these data, stance phase occurrence was determined. Once the stance phase was determined, the rearfoot motion, pronation time, and pronation velocity were calculated from data collected with a flexible goniometer. Discrete measurements from the analog patterns were identified to facilitate parametric analysis. Variables measured included peak impulse loading, peak power, rearfoot motion, pronation time, and pronation velocity. Appendix B contains definitions of the subject test variables.

Questionnaire. After each subject's biomechanical test, a brief survey addressing comfort parameters was administered. Immediately after testing, subjective responses were obtained from each subject regarding the relative comfort of each boot worn. One specific question rated the comfort level on a scale from 1 (extremely uncomfortable) to 5 (extremely comfortable).

Results and Discussion

Boot Impact Tests

The physical tests were conducted to evaluate the cushioning and material characteristics of the footwear. Figures 1 and 2 display the material thickness of each boot tested. This baseline information was needed to determine the original thickness of the material prior to impact. Impact tests that measured peak *g* at the forefoot and the heel of the footwear revealed that the Bates Lite and Northlake boots had values that were approximately half those of the military boots (see Figures 3 and 4). The Bates Lite boot obtained the lowest heel peak *g* score (15 peak *g*) and the leather combat boot obtained the highest heel peak *g* scores (33 peak *g*). The Northlake boot and the Bates Lite boot scored the lowest for forefoot peak *g* (19 peak *g*), and the jungle boot scored the highest (38 peak *g*). These results suggest that the Bates Lite and Northlake boots are better suited to absorb the shock applied to the heels and the forefeet in comparison with the other footwear tested. Conversely, the combat boot and jungle boot transfer more shock to the body during activity when compared with the other footwear tested.

Figures 5 and 6 show the time that the impact takes to reach peak g for the heel and forefoot. The Northlake boot had the longest heel and forefoot time to peak g, and the leather combat boot had the shortest time. A slower deceleration of the foot as it contacts the ground will lessen the shock the body experiences (Clarke, Frederick, & Cooper, 1983). Thus, the Northlake boot is a better shock absorber.

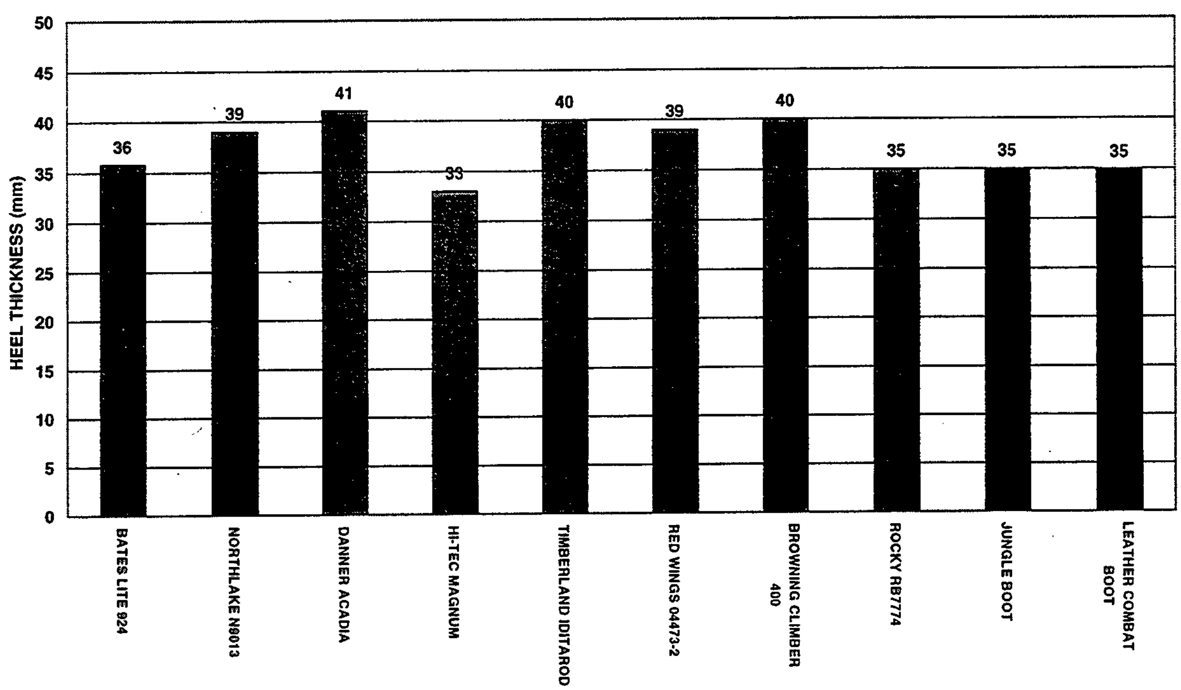

Figure 1. **Heel thickness.**

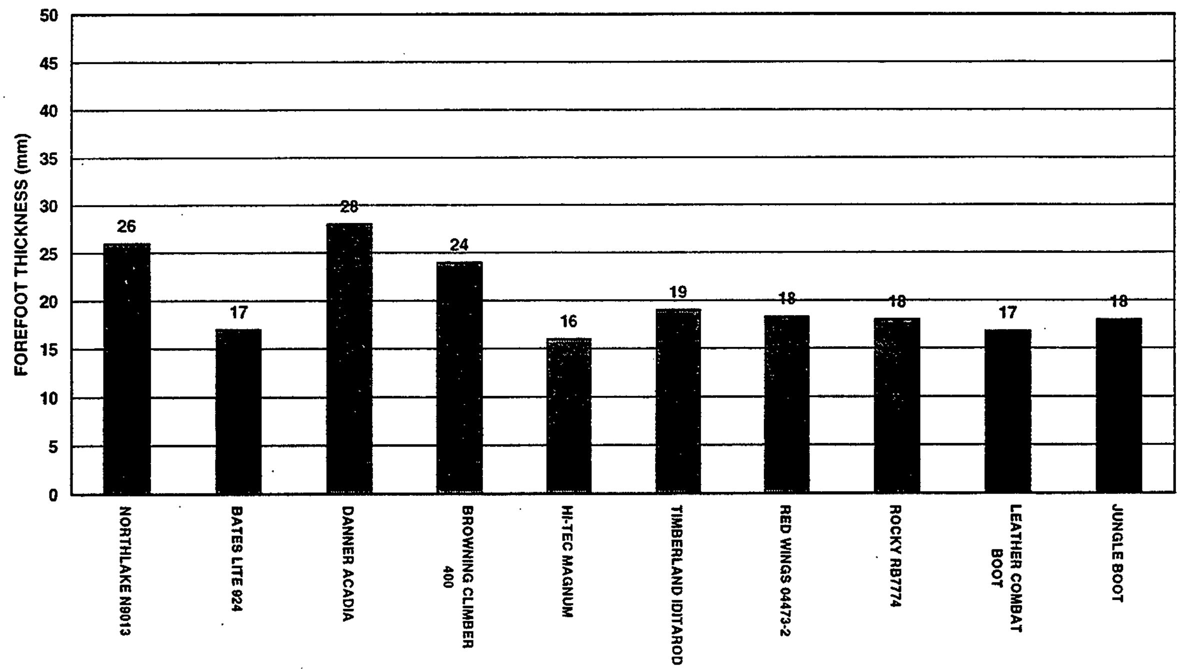

Figure 2. **Forefoot thickness.**

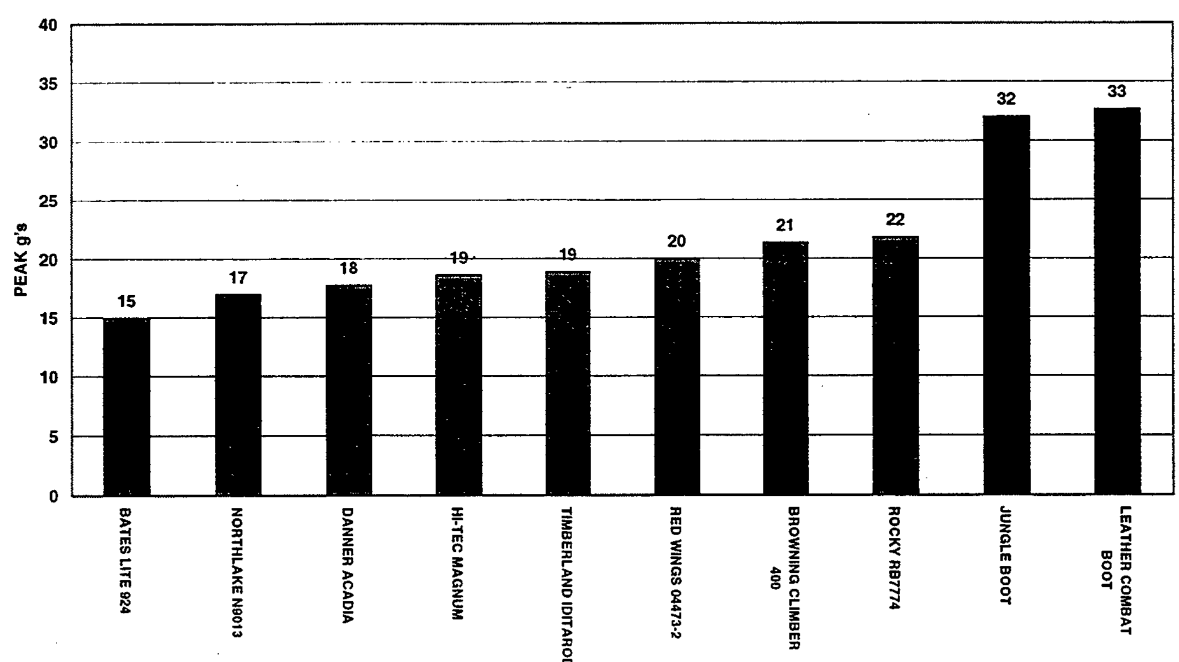

Figure 3. **Heel peak *g* scores.**

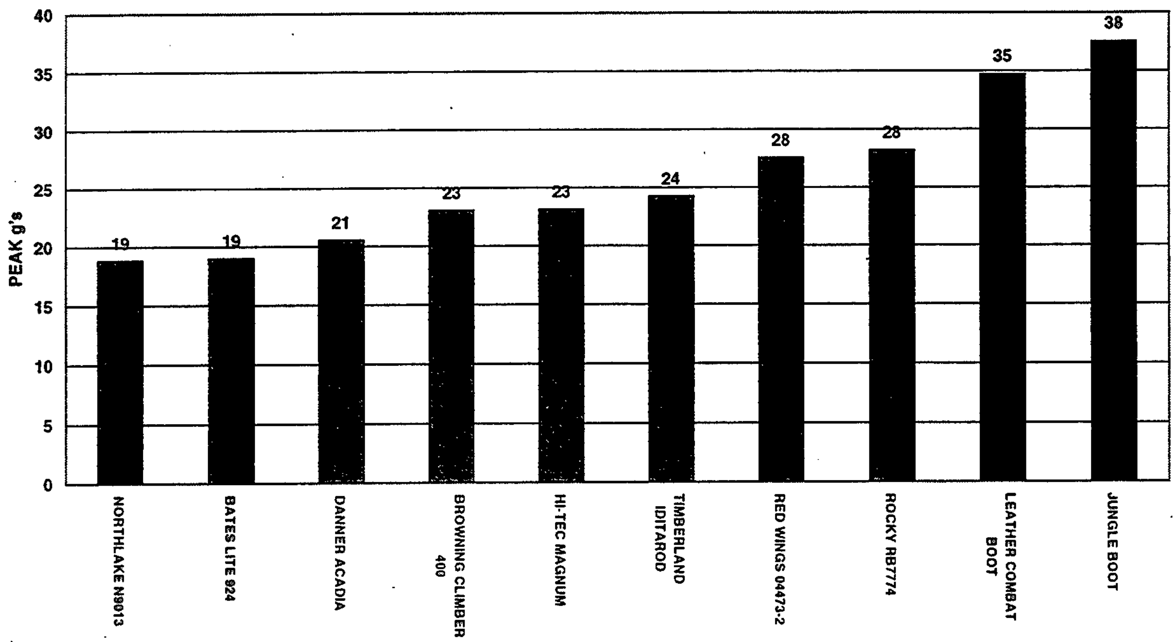

Figure 4. **Forefoot peak *g* scores.**

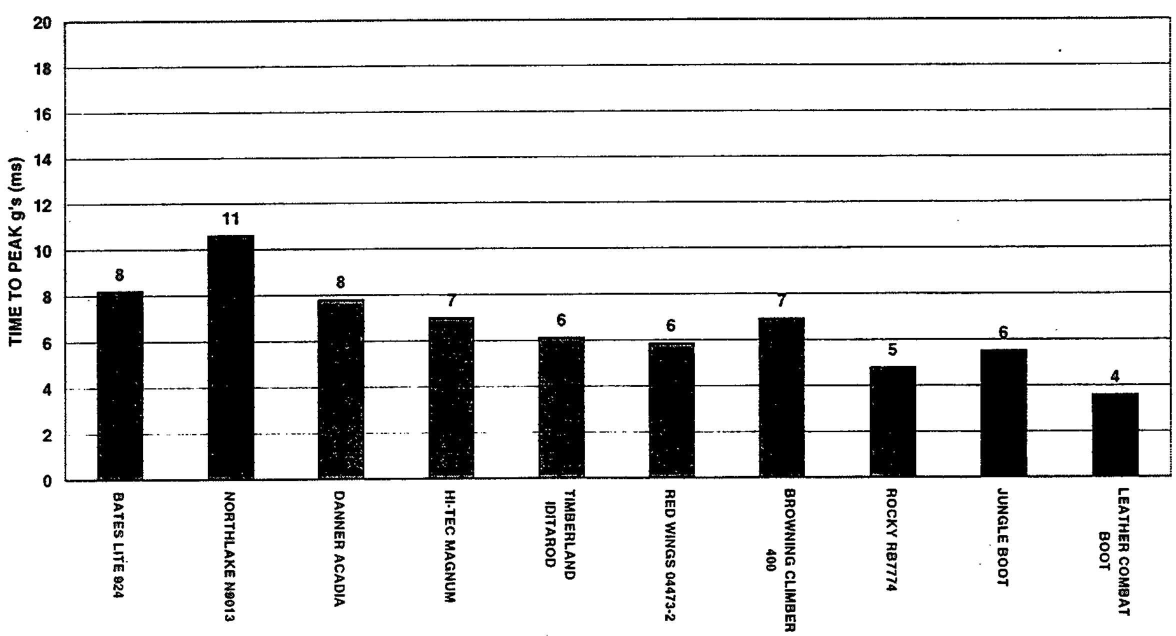

Figure 5. **Heel time to peak *g*.**

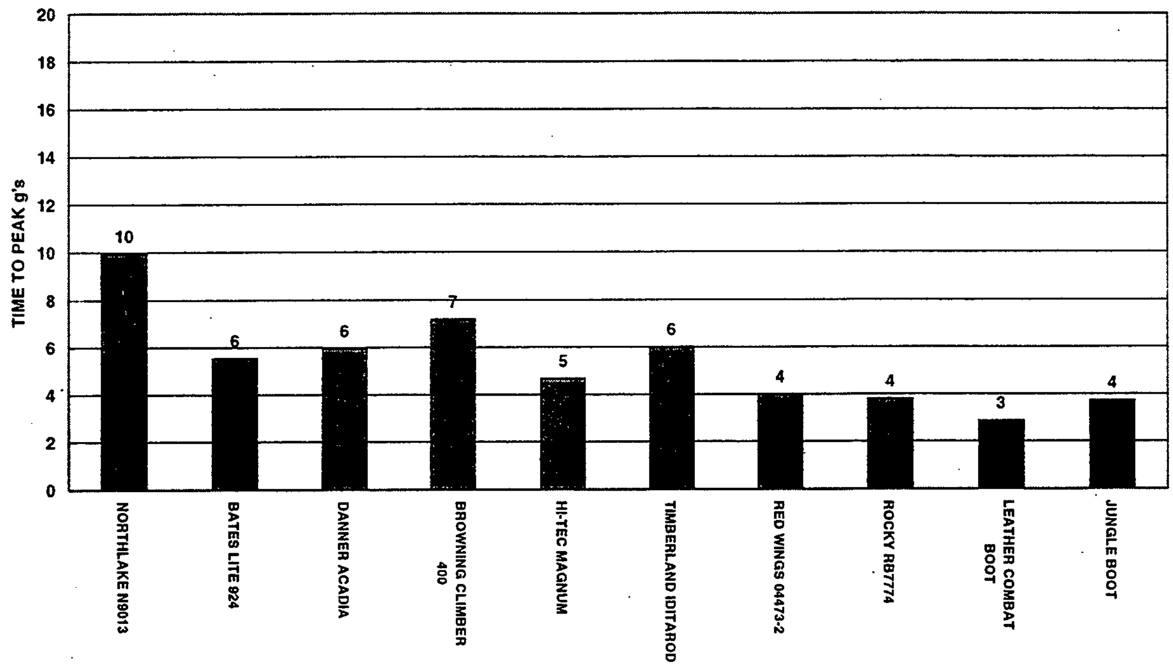

Figure 6. **Forefoot time to peak *g*.**

For materials of equal thickness, a greater force penetration will also have a greater time to peak *g*. However, if the material is too thin it may "bottom out," or become fully compressed and lose its shock absorbing characteristics altogether. The percentage of compression of the material during impact is detailed in Figures 7 and 8. The Northlake boot had the highest percentage of heel and forefoot penetration compared with the leather combat boot, which had the lowest percentage of heel and forefoot penetration. Greater penetrations are interpreted as indicating better shock absorbency at impact (Bates, Sawhill, & Hamill, 1980). Functionally, this means that the Northlake boot was better at absorbing shock by allowing the foot to sink deeper into the material, which required more time and thereby decreased the peak impulsive force.

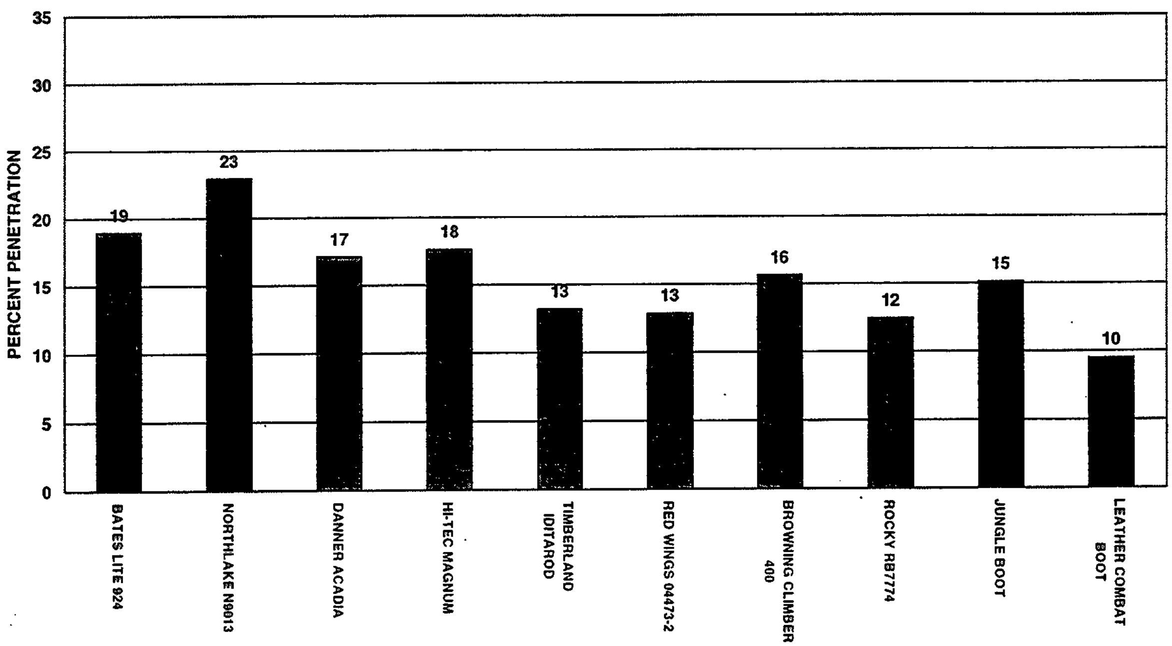

Figure 7. **Percentage heel penetration.**

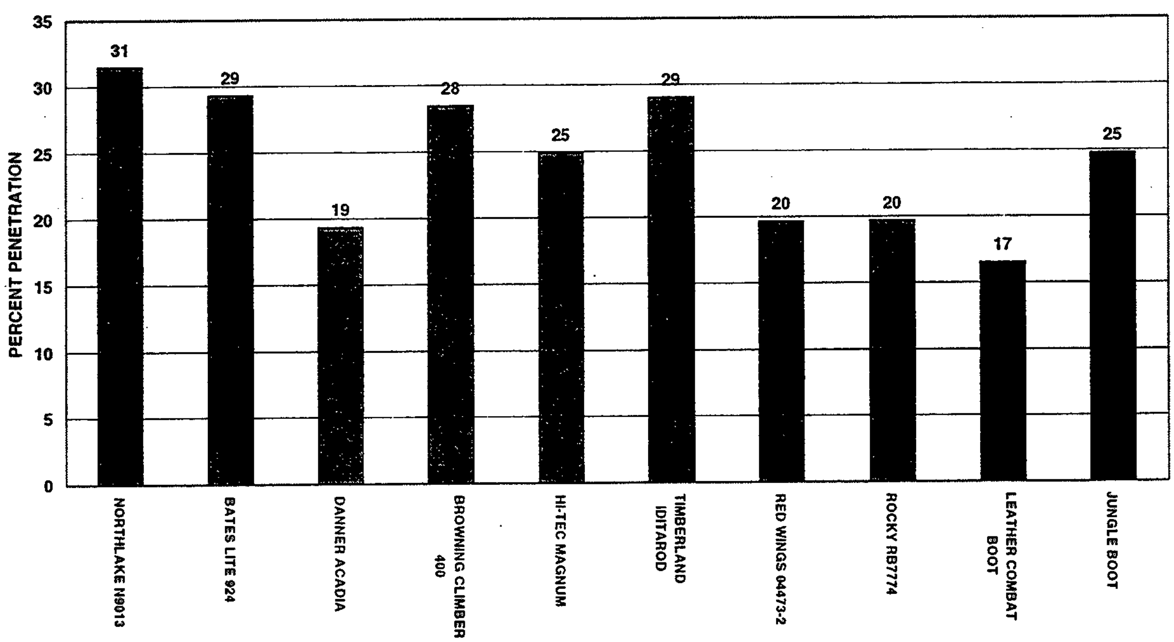

Figure 8. **Percentage forefoot penetration.**

Figure 9 shows heel peak force. The Bates Lite boot absorbed the lowest amount of force at the heel (1247 N) compared with the leather combat boot, which absorbed the highest amount of force at the heel (2722 N). Forefoot peak force is summarized in Figure 10. The Northlake boot absorbed the least amount of force at the forefoot (1566 N), while the jungle boot absorbed the greatest amount of force at the forefoot (3131 N). Theoretically, the boot that absorbs a greater magnitude of this force will transfer more shock to the body. Therefore, it is desirable to wear a boot with a lower peak force score.

The percentage of energy return is a test of the rebound height of the weighted shaft of the impacter following impact. A higher percentage of energy return indicates that much of the energy at impact is preserved and returned at the end of the collision. Figures 11 and 12 display the percent of energy return for each of the boots tested. The Northlake boot had the highest percentage of heel and forefoot energy return, scoring 50% on each of the tests. The leather combat boot had the lowest percentage of heel energy return (27%), and the Timberland Iditarod and Rocky boots had the lowest percentage of forefoot energy return (27%). Theoretically, more energy would be expended by those wearing boots with the lowest percentage of energy return values. Energy expenditure differences might be revealed in oxygen uptake or heart rate values (Hamill & Bensel, 1996). Thus, a boot with a high energy return is desirable because more energy is returned to the subject's leg.

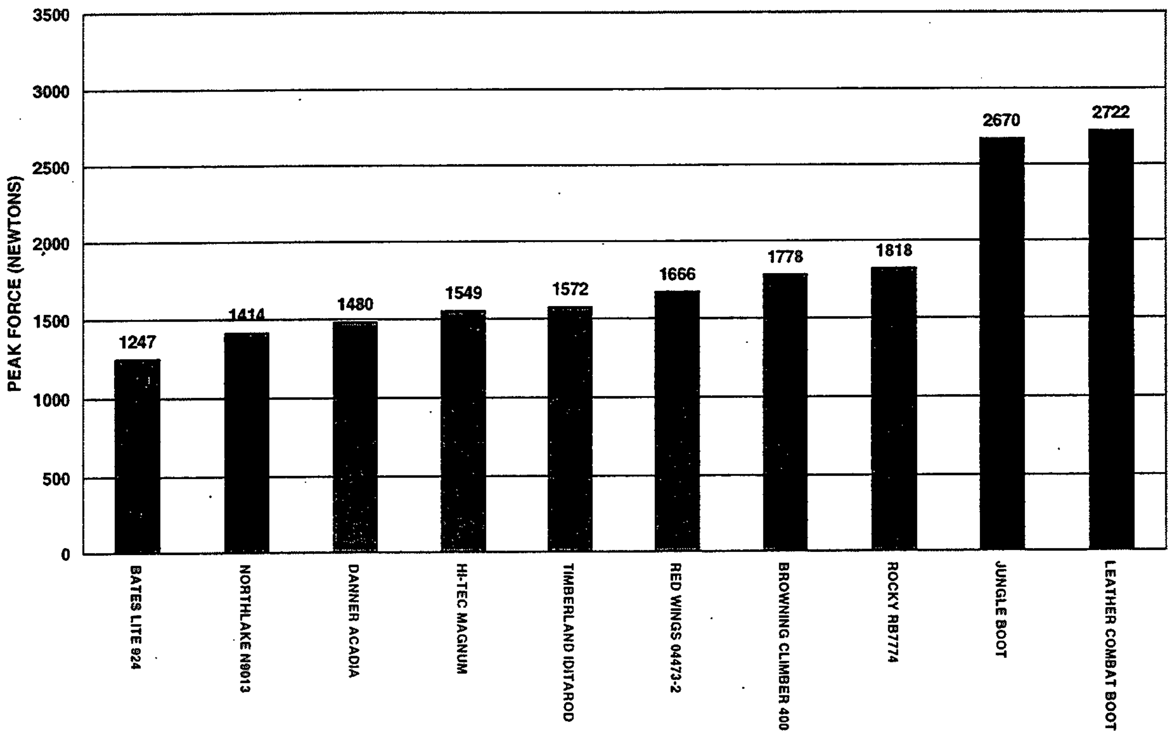

Figure 9. Heel peak force.

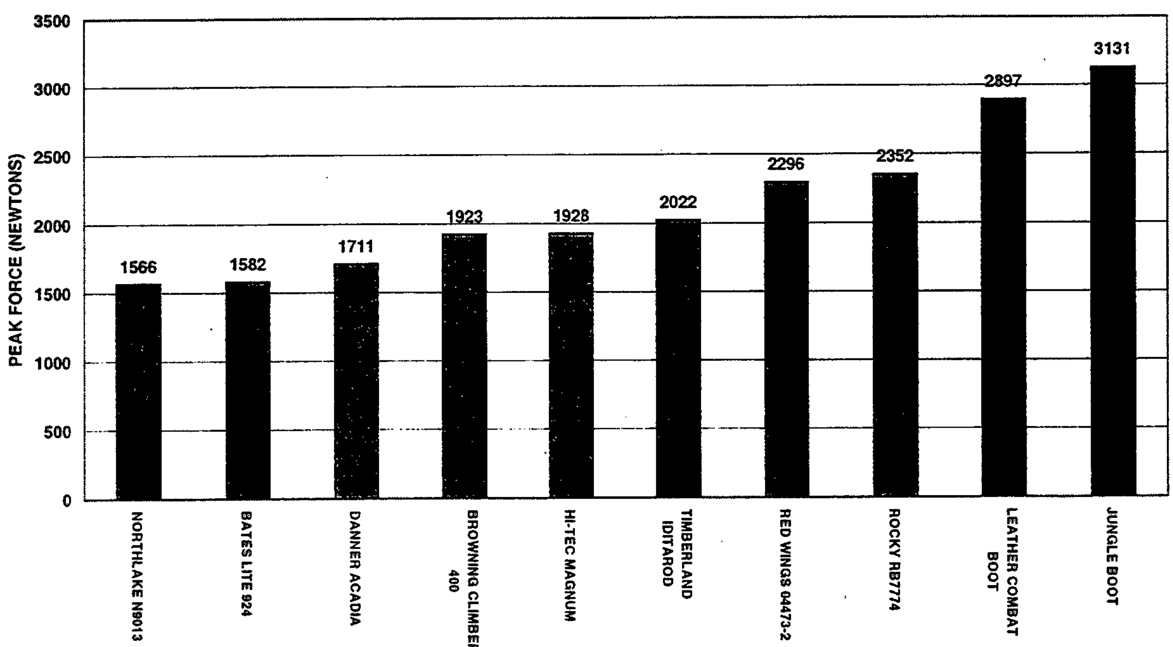

Figure 10. Forefoot peak force.

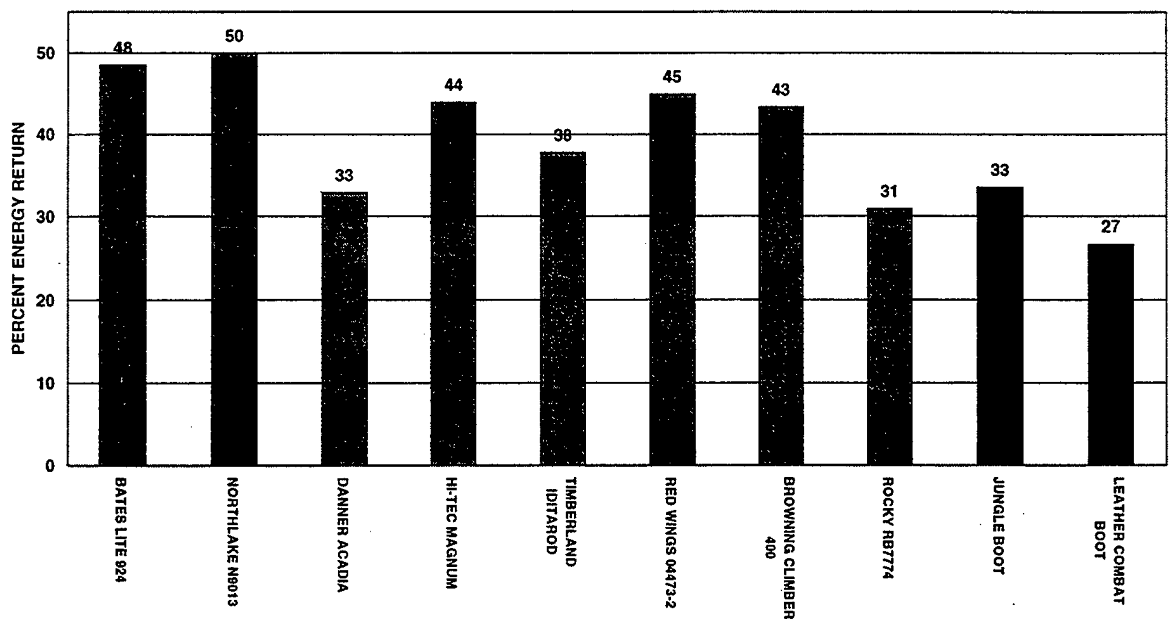

Figure 11. **Percentage of heel energy return.**

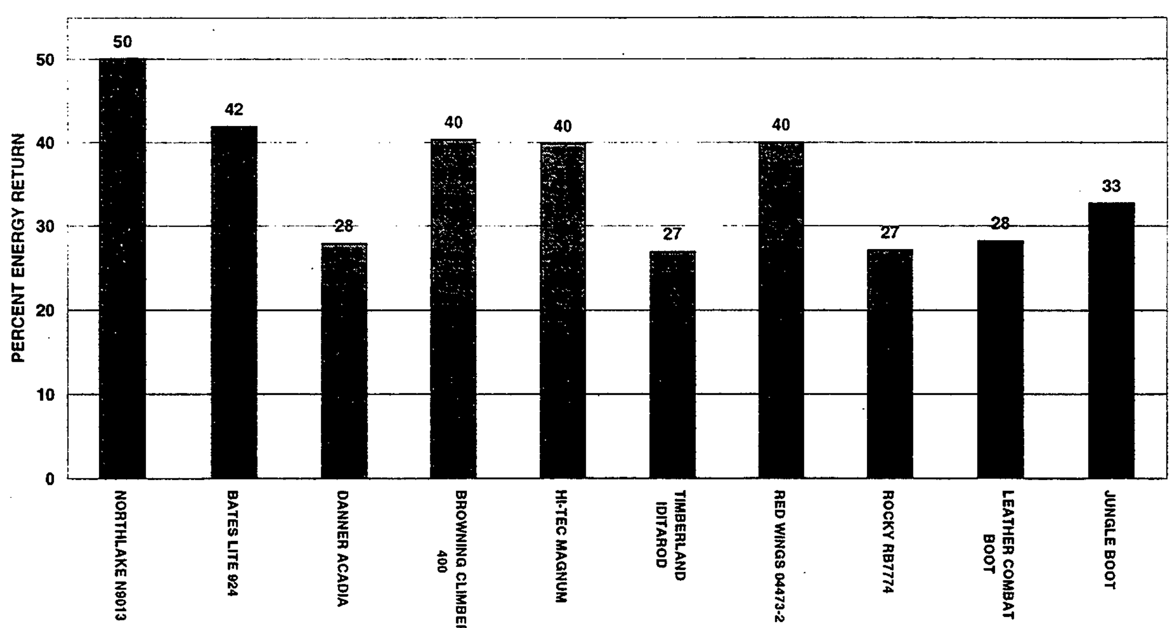

Figure 12. **Percentage forefoot energy return.**

Development of Prototype Boots

Two prototype boots were designed for testing with existing jungle boot uppers and revised soles. Polyurethane was selected as the primary sole material based on the cushioning characteristics of the Bates Lite boot in the physical tests. Notably, the only other boot with equivalent shock absorption, the Northlake boot, has a hallowed out rubber sole. However, this sole design may have affected the durability of the boot. The prototype boot had a quarter-inch polyurethane insole incorporated into the design of the boot for added comfort. Both boots also had a polyurethane midsole, which was added to improve the shock absorbency characteristics of the boot. The only difference in the 2 prototype boots was in the outsole material selected. One boot had a polyurethane outsole, while the other boot had a rubber (Vibram) outsole.

Subject Performance Tests

The two primary goals of boot design are shock absorption and stability. These are competing requirements. A boot with a large amount of shock absorption may not provide a stable base of support. Conversely, a boot with a high degree of stability may not have much shock absorption. Therefore, an optimal boot design would contain an ideal combination of the following requirements: (1) peak impulse-loading, (2) peak power, (3) rearfoot motion, and (4) pronation velocity.

Peak impulse-loading scores for each boot are presented in Figure 13. The Asolo boot scored the lowest value (55.5 ns) indicating the greatest shock absorbency of all the boots tested, with the Bates Lite boot having the next lowest value (56.5 ns).

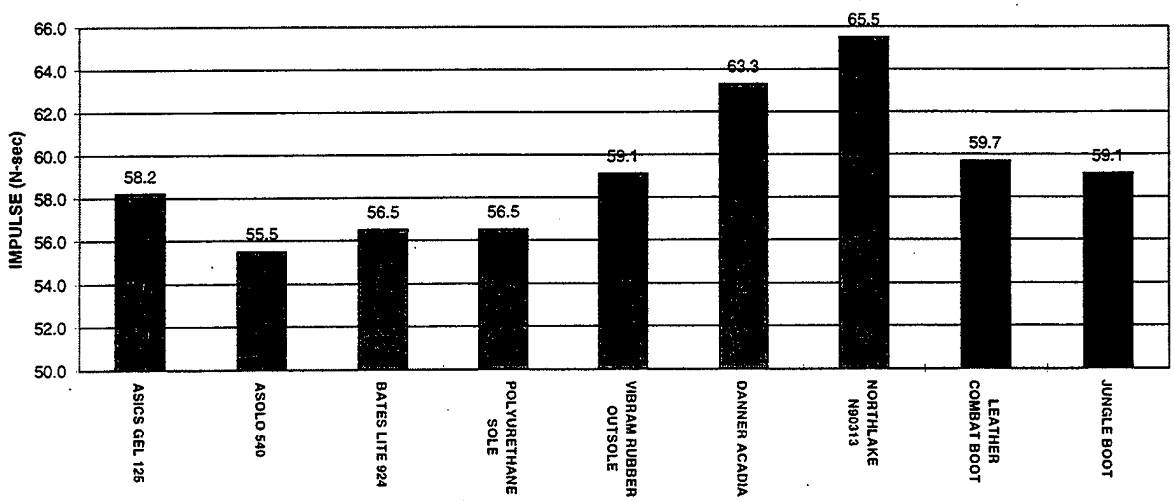

Figure 13. **Peak impulse-loading (10 subject average).**

Another test important in the determination of shock absorbency is peak power (see Figure 14). Peak power is an indication of the muscular effort required by the subject. The Asolo boot had the lowest peak power score, requiring the least amount of muscular effort from the subject to obtain the desired shock absorbency. Overall, the greatest shock absorption and lowest power requirements were obtained with the Asolo boot, the Bates Lite boot, and the polyurethane prototype boot. The least shock absorption and highest power requirements were obtained with the Northlake, Danner Acadia, and combat boots.

Rearfoot motion and pronation velocity are important factors in determining footwear stability. Rearfoot motion is the total amount of eversion from foot contact to maximum pronation (see Figure 15). The Danner Acadia boot obtained the lowest rearfoot motion score, minimizing the amount of eversion the subject experienced. Pronation velocity, the angular rate of pronation, calculated from foot contact until maximum pronation, is another determinant of stability. A lower pronation velocity is known to reduce rates of injury (Hlavac, 1977; James et al., 1978). The Danner Acadia boot had the lowest pronation velocity, indicating more stability. Overall, the most stability was achieved with the Danner Acadia boot, the combat boot, and the Bates Lite boot.

The boot with the optimal combination of shock absorption and stability was the Bates Lite boot. This boot also scored the highest comfort level subjective rating, followed by the Asics running shoe and the polyurethane prototype boot (see Figure 16).

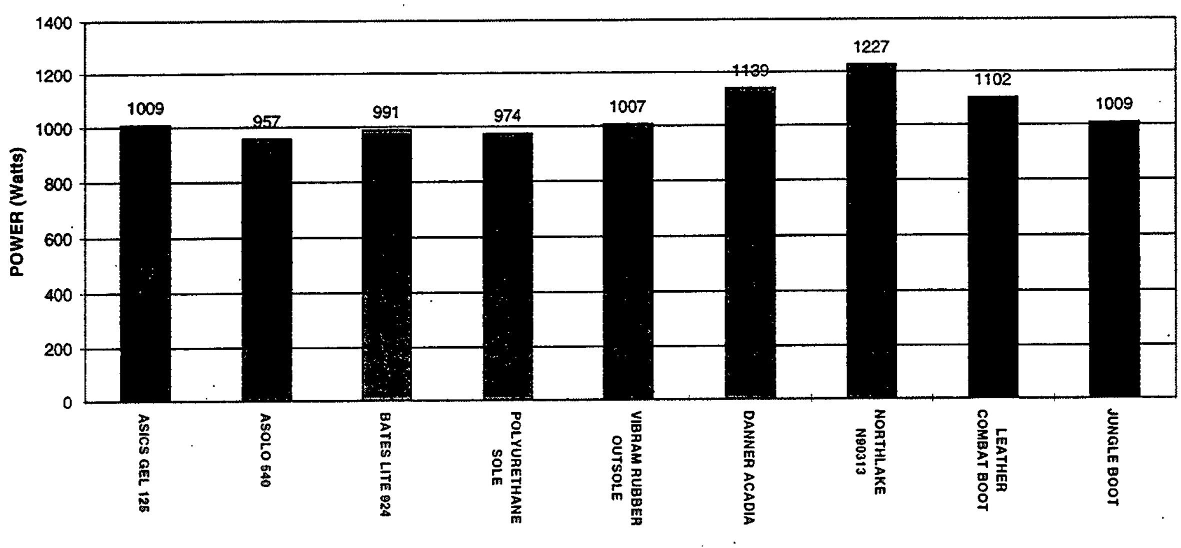

Figure 14. **Peak power (10 subject average).**

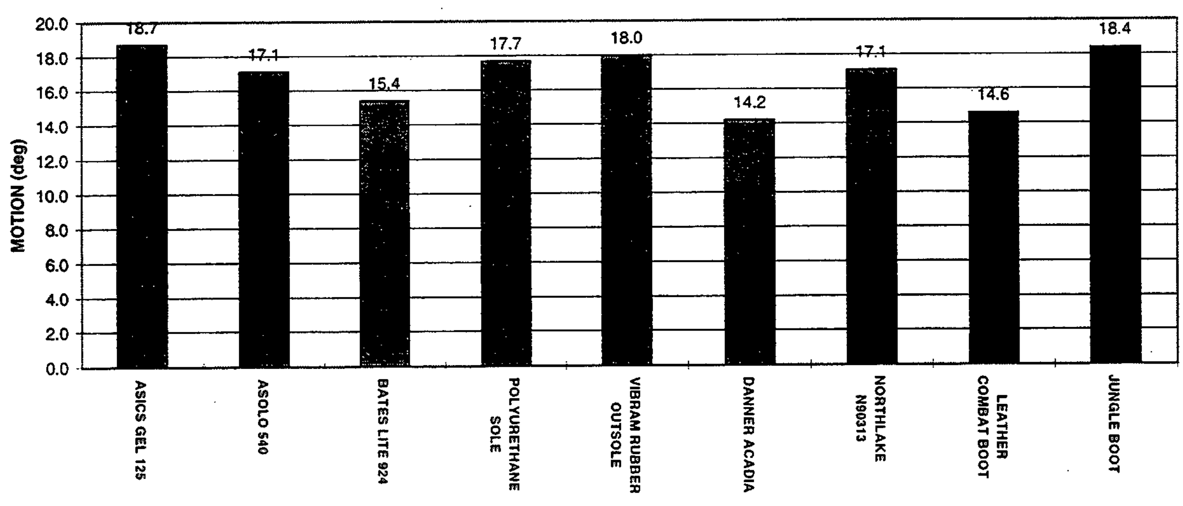

Figure 15. **Rearfoot motion (10 subject average).**

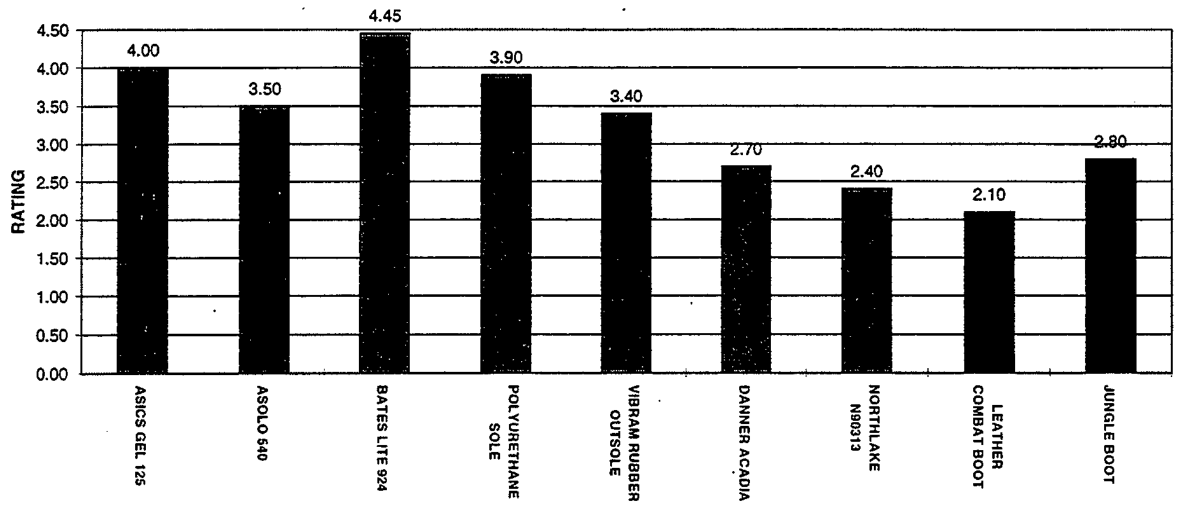

***Figure 16.* Subjective rating of boots.**

Conclusion

Data derived from the boot impact tests revealed that all of the commercially available boots tested superior to the standard-issue jungle and leather combat boots. According to the subject biomechanical performance tests, the greatest shock absorption and lowest power requirements were obtained with the Asolo boot, the Bates Lite boot, and the polyurethane prototype jungle boot. The most stability was achieved with the Danner Acadia boot, the combat boot, and the Bates Lite boot. It is important to note that the jungle boot was markedly improved in each of the subject test parameters with the addition of the polyurethane sole (i.e., polyurethane prototype boot). Moreover, the polyurethane prototype boot scored high in the subjective ratings of comfort. Also, it is worthwhile to acknowledge that several of the boots tested yielded biomechanical profiles similar to those of a high-performance running shoe (Asics Gel 125). Our findings suggest that currently available boots offer superior features over the standard-issue military boots. This study illustrates that several optimal characteristics from various commercially available boots can be combined to create a military prototype boot which surpasses that which is currently in use.

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Appendix A

Physical Test Definitions

Peak *g*
Peak *g* describes the ability of the item tested to absorb the shock that is applied to it. The higher the "*g*" score, the more shock the body will experience during activity.

Time to peak *g*
Time to peak *g* describes the amount of time that the result of the impact takes to reach peak *g*. A slower deceleration of the foot as it contacts the ground will lessen the shock the body experiences.

Peak force
Peak force is the maximum amount of force that a material absorbs during impact. The interpretation of this parameter is that the higher the force, the more shock the body will experience during activity. It is desirable to wear a boot with a lower peak force score.

Percentage penetration
Percentage penetration is the percentage of compression of the material (during impacting) from its original thickness. Greater penetrations are interpreted as indicating better shock absorbency at impact. However, if a material is too thin, it may "bottom out."

Percentage of energy return
Percentage of energy return is the amount of energy that remains after the impact has occurred. Thus, a boot with a high energy return is desirable because more energy is returned to the subject's leg.

Appendix B

Subject Test Definitions

Peak impulse-loading
Peak impulse loading is an indication of the shock absorbency characteristics of the footwear. A lower value indicates better shock absorbency.

Peak power
Peak power is an indication of the muscular effort required by the subject. A larger peak power means the subject will need to provide more muscular effort to obtain the desired shock absorbency.

Rearfoot motion
Rearfoot motion is the total rearfoot motion (eversion) from foot contact to maximum pronation. Limited rearfoot motion is desirable for stability.

Pronation velocity
Pronation velocity is the angular rate of pronation, calculated from foot contact until maximum pronation occurs. A lower pronation velocity indicates more stability and is known to reduce rates of injury.

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13. ABSTRACT *(Maximum 200 words)*

A critical item to USMC standard military issue is the combat boot. Military requirements demand a boot that is comfortable, durable, and enhances the movement capabilities of the soldier. This study evaluated the biomechanical properties of commercially available boots and provided recommendations for optimal design. The evaluation included physical tests of the footwear material characteristics and biomechanical tests using human subjects. A survey addressing comfort parameters was administered to each subject. Boot impact tests revealed that all of the commercially available boots tested superior to the standard-issue jungle and leather combat boots. On the performance tests, the greatest shock absorption and lowest power requirements were obtained with the Asolo 540 boot, the Bates Lite 924 boot, and the polyurethane prototype boot. The greatest stability was achieved with the Danner Acadia boot, the leather combat boot, and the Bates Lite boot. The jungle boot improved markedly in each of the test parameters with the addition of the polyurethane sole (polyurethane prototype boot). Findings suggest that commercially available boots offer superior features over standard-issue military boots. This study illustrates that optimal characteristics from commercially available boots can be combined to create a military prototype boot surpassing those in current use.

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