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THE RELATIONSHIP OF FOOT SHAPE AND SENSITIVITY TO COMFORT OF SHOE-INSERTS

THE UNIVERSITY OF CALGARY

Human Performance Laboratory
Faculty of Kinesiology

THE RELATIONSHIP OF FOOT SHAPE AND SENSITIVITY TO COMFORT OF SHOE-INSERTS

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EXECUTIVE SUMMARY

Army personnel are generally very physically active individuals performing various different physical activities. The choice of appropriate footwear is essential for any physical activity and any specific individual. It is speculated that comfortable footwear will optimize an individual's performance and reduce the frequency of traumatic and overuse injuries. Although it is generally accepted that individuals with different foot and leg characteristics require subject specific functional footwear, this option is not readily available to army personnel. This is probably due to the fact that footwear requirements for specific foot and leg characteristics are not available. For example, if an individual has a high arched foot, do they require footwear with a high or low arch? To increase performance and decrease injuries it is necessary to determine which specific characteristics of the human foot or leg determine the reaction to different footwear and insert variables. Ultimately, this information should be used to prescribe appropriate footwear to specific individuals. This study is a first step in understanding this complex set of questions.

The purpose of this study was to determine anthropometric and sensory factors, which may predict the short-term reaction of the foot to a set of selected shoe-insert constructions.

A total of 106 male subjects volunteered in this project (mean age 23 years). Measurements of foot shape, leg characteristics, and foot sensitivity were conducted on each subject. Each subject was then asked to perform walking and running trials on an indoor track while wearing Combat Boot Mark III in which an insert was placed. The trials were conducted to subjectively evaluate the comfort of ten different shoe inserts, which differed in material and structure. The three different materials properties evaluated were soft elastic, hard elastic and soft viscous, which were varied systematically in the fore- and rearfoot regions. The structural differences evaluated included a spherical vs. flat heel and a high vs. low arch. Relationships between the insert characteristics and the individual subject characteristics, which may have had an influence on comfort, were analyzed.

The two inserts that received the highest comfort rating in this study had similar materials and structure. Both had a high arch support, a spherical heel shape (heel cup), soft and elastic material in the forefoot region, and soft material in the heel region. The only difference between these two inserts was elasticity of the material used in the heel region, i.e. elastic material versus viscous material. The insert with the lowest comfort rating had a hard insert in the forefoot region. This unique feature was obviously disliked by the majority of the subjects tested. It indicated an important role of forefoot "bedding" for the comfort of the shoe. Therefore, an insert without soft forefoot "bedding" is not recommended in terms of comfort.

Certain attributes of the boots used in this investigation were uncomfortable for some of the subjects. It was found that more than half of the subjects complained about the pain and/or discomfort caused by the high pressure in the dorsal region when they wore the army boots provided. One other factor, which some subjects complained about during walking, was the high boot stiffness at the forefoot. The forefoot region of the boots was difficult to bend during walking, but not during running.

Specific insert results

The insert characteristics of importance throughout the study for high comfort assessment were

- soft material properties,
- spherical heel and
- an elastic forefoot material.

In addition to these preferred characteristics

- the elastic heel was slightly preferred over the viscous heel and
- the high arch was slightly preferred over the low arch.

However, these latter two variables (visco-elasticity of the heel and arch height) were not as important as the primary variables (soft insert material, spherical heel and elastic forefoot material) in terms of preference by the subjects. Visco-elasticity of the heel and arch height are variables that seem not as important. It is speculated that good results for large subject groups can be achieved with viscous or elastic heels and with high or flat arch supports.

However, there are certain foot/shoe characteristics that do not fit into this general solution. Whenever the heel fit is tight, the hard material is preferred over the soft material. However, selecting a wider heel insert can solve this problem. Based on the results of this study, there is no reason to prefer hard over soft.

The viscous heel was preferred by subjects with a tight heel fit, substantial tibial-rotation and high vibration sensitivity of the hallux. At this point in time, there is no obvious criterion for this grouping of subjects that prefer viscous heels.

The two confirmed factors that preferred elastic heels were poor subtalar joint alignment and good [straight] Q-angle. Again, there is no obvious pattern for this grouping. This leads to the suggestion that the variables that have been shown as different for the different heel materials should be studied further. At this point in time, the conclusion would be that both solutions (elastic and viscous heels) are acceptable.

The spherical heel was clearly preferred over the flat heel. There were only a few, not confirmed factors, which suggested that the flat heel may be more advantageous, however, based on the results of this study the spherical heel is the preferred choice for an insert.

With respect to the arch in the insert, subjects generally preferred an arch. However, there were two groups, which did not agree with that assessment. Subjects with a poor Q-angle and subjects with a poor subtalar joint alignment were those, which preferred a low arch. That could be interpreted as an indication that poor joint alignment is associated with the preference of low insert arches.

The material property of choice for the forefoot was elastic. However, subjects with two specific characteristics preferred viscous forefoot material. Subjects with a bad Q-angle and subjects with a high tactile sensitivity at the metatarsal heads preferred viscous forefoot materials. If one compares this with the fact that viscous forefoot materials demand about 1 to 2% more energy during locomotion one should avoid viscous materials for the forefoot except for specific sub-groups (high Q-angle and high tactile sensitivity at the metatarsal heads). It is interesting, however, in this context that the opposite groups, those with the good Q-angle and those with the low tactile sensitivity at the metatarsal heads had just the opposite preferences, they preferred elastic forefoot materials.

Speculation-Concepts

In the attempt to group the results to formulate speculations for future research and appropriate insert construction, the following concept/speculations can be made:

1. If subjects have a poor alignment of the skeleton (heel, subtalar joint, tibial torsion, Q-angle) they are best served with a soft and viscous insert with no medial arch support. This statement is supported by 5 out of 6 results in the summary table. The statement about soft material and low arch seems to be strong, the statement about viscous material is less strong. In support of this speculation one could argue that people with poor skeletal alignment do not want anything resisting their foot movement. Thus, they prefer soft and viscous materials with no arch support.

2. Subjects that are highly sensitive (tactile and vibration) prefer soft and viscous materials. Subjects that have a low sensitivity (tactile and vibration) prefer elastic materials and a high arch. These are two strong speculations, which can be supported by functional considerations. Subjects who are highly sensitive don't need extra input signals. However, subjects who are not highly sensitive may need strong input signals (produced by the elastic material and the high arch).

The variables describing the shoe fit described results, which in some cases corresponded to strong preferences for specific constructions. However, problems created by too loose or too tight fit in the heel or at the toe are subject specific and can be resolved by changing the shoe (e.g. by choosing a bigger size). They should and did not provide any systematic results that can be explained functionally. Thus, they should not be considered further as determining variables. However, they should be included as constraint variables for further studies.

The first step in the program to determine factors important for footwear of military personnel has shown some interesting results and resulted in some strong speculations for grouping of shoe-foot characteristics. The next step should include dynamic and long-term experiments in which specific speculations and hypotheses are tested.

INTRODUCTION

The effects of footwear on the human body are obvious in many human activities. Footwear influences the frequency of overuse injuries, the energy expenditure during a given task and the comfort level of the users significantly. The effects of footwear on the human body are rather obvious in sport activities but have not been addressed frequently in the literature for other daily/work activities. Applications for activities where footwear seems rather important include the work place environment of fireman or oil-rig workers and the activities of soldiers.

Factors which determine the occurrence of overuse injuries, the energy requirements and/or the comfort aspects include weight, flexibility, fit and shoe-inserts. The effects of weight and flexibility have been widely studied. However, the effects of shoe-inserts on performance or injury have not been studied systematically. It is known, for instance, that individual feet react differently to variations of shoe-inserts but it is not known which specific characteristics of the human foot or leg determine the reaction to a shoe-insert. Furthermore, it is not known whether the important criteria are mechanical (e.g. arch height or foot flexibility) or sensory (e.g. sensitivity of the plantar surface of the foot).

For activities which are typical for army personal the choice of an appropriate shoe is essential. However, the criteria for this choice are not established. Consequently, many soldiers have inappropriate footwear which may result in unnecessary overuse injuries, reduced performance and discomfort (which is typically associated with fatigue and/or pain). The understanding of this complex set of questions is not simple and it is proposed to approach the topic in a stepwise procedure. This study is the first step which will concentrate on the shoe-insert to identify which solutions of shoe inserts can be applied with a high probability of success.

The purpose of this study was to determine the anthropometric and sensory factors which may predict the short term reaction of the foot to a set of selected shoe-insert constructions.

It was hypothesized that soldiers who are outfitted with army boots constructed and fitted using the results of the proposed study will have less overuse injuries, have improved performance and feel more comfortable in their daily activities.

LITERATURE REVIEW

Overuse injuries

Overuse injuries represent the largest percentage of sports-related injuries among athletes (O'Toole et al. 1989) and training-related injuries in military recruits that require medical treatment (Bennell and Brukner 1997). Current estimates are that up to 60% of runners will experience an injury that will limit their activities (Brody 1980, Jacobs & Berson 1986, Lysholm & Wiklander 1987, Marti 1988, Sheehan 1977). Most of these injuries are lower limb injuries including such maladies as patellofemoral disorders, shin splints, Achilles tendinitis, plantar fasciitis and various stress fractures. Lower limb injuries were reported to be the greatest source of medical problems during basic military training (Ross 1993). Increased lower limb injuries had the consequence of increased medical discharges, as reported by the British Army (Jefferson 1989). Increased training volume was reported to be directly related to the increased occurrence of overuse injuries (O'Toole et al. 1989). The pathogenesis of these overuse injuries is still not understood. However, the development of persistent pain in the lower limb following prolonged sustained intensive physical activity was reported to occur before the injuries (Volpin et al. 1989). The common causes of overuse injuries were suggested to include training errors and biomechanical factors (Rzonca et al. 1988, Micheli 1986). In the lower extremity, risk factors include inappropriate progression of the rate, intensity and duration of training; anatomic malalignment; muscle-tendon imbalances of strength, endurance, or flexibility; shoe wear; surface; and pre-existent disease states.

Effect of shoe and shoe insert

It has been suggested that impact forces during running and other activities are associated with the development of injuries and that the improvement of running shoes and surfaces would reduce the frequency of impact related injuries (Miller, 1978; Nigg, 1978; McMahon and Green, 1979; Cavanagh and Lafortune, 1980). In a prospective study of the effect of training shoe type on the incidence of overuse injuries among infantry recruits, it was found that recruits who trained in basketball shoes had a lower incidence of overuse injuries of the feet than recruits who trained in infantry boots (Finestone et al. 1992, Milgrom et al. 1992). Although it was not measured directly, the effect of improved shock attenuation of vertical impact loads was speculated to account for the reduction of overuse injuries.

It has been widely reported that shoe inserts are an effective interventional modality for the relief of discomfort to the feet associated with a variety of orthopedic disorders or conditions. A well constructed shoe insert can provide not only shock attenuation, but also appropriate arch support, better fit of the shoe and better control of rearfoot motion (Kilmartin and Wallace 1994, Gross and Napoli 1993). Shoe inserts have been shown to be effective in adjusting the biomechanical-variables associated with running injuries and reducing the effect of high stresses produced by running activities. Shoe inserts have been successful in the treatment of lower limb osteoarthritis (Keating et al. 1993, Sasaki and Yasuda 1987). In a study of conservative management of metatarsal and heel pain in the adult foot, D'Ambrosia (1987) suggested that foot orthotic devices seem to be the most useful in the treatment of metatarsal and heel pain. It has been found necessary to prescribe orthotics in almost all cases of chronic problems to institute permanent relief. Shock absorption was suggested as the most important property of shoe insert materials (Lewis et al. 1991). The use of a shock absorbing shoe insert was shown to reduce the incidence of soreness in the Achilles tendon, calf and back (Fauno et al. 1993). Viscoelastic shoe inserts have been shown to be effective in reducing back, leg, and foot pain among adults who spend the majority of each work day standing (Basford and Smith 1988, Tooms et al. 1987), and in aerobic dancers (Clark et al. 1989). However, most of the studies in the past have been focused on only one single variable. The knowledge about the influence of shoe inserts on the overuse injuries and shoe comfort is scattered. A systematic study evaluating shoe inserts with various material properties and shapes is missing. This study was a primary step in attempting to fill this void.

Shoe comfort and overuse injuries

Individuals with overuse injuries on the lower limbs were observed to have persistent pain/discomfort before injury occurs (Volpin et al. 1989, Ballas et al. 1997). The pain/discomfort may serve as a signal to indicate that injury may be a long-term consequence. A semiflexible insert material was shown to reduce the discomfort in athletes and was suggested to reduce the overuse injury as well (Richie and Olson 1993). Repeated loading of the foot and excessive tension of the plantar fascia have been implicated by several authors as a cause of plantar fasciitis which results in symptomatic heel pain and inflammation (Campbell and Inman 1974, Newel and Miller 1977, Kwong et al. 1988). In order to avert such pathological results, it has been proposed that the objective of orthotic intervention is to resist depression of the foot's arch during weight bearing through skeletal support, thereby decreasing tension in the plantar aponeurosis (Campbell and Inman 1974). When considering shoes, and specifically shoe inserts, increased comfort may simply indicate less risk of overuse injuries. Shoe comfort is one of the most important factors in selecting footwear. Every individual can chose a pair of shoes that is comfortable to wear despite the fact that the definition of and the scale to quantify shoe comfort is still not clear. Shoe comfort with respect to various types of shoe inserts has not been studied comprehensively, neither has its correlation to the shape, dimension and sensitivity of the foot.

Foot structure and comfort

The influence of shoe inserts on motion of the lower limbs may depend on the structure of the foot. There have been several studies that showed changes in joint motion and mechanics due to the use of different shoe inserts (Bates et al. 1979, Eng, & Pierrynowski 1994, Brown et al. 1995, Cornwall & McPoil 1995). There is evidence showing that the dynamic motion of the foot is, to a certain degree, related to the structure of the foot (Fox, 1950, Rodgers, 1995, Duckworth, 1985, Hamil et al. 1989, Nigg et al. 1993, Cavanagh et al. 1997). Some studies suggested associations between foot structure and specific overuse injuries, such as patellar pain (Powers et al. 1995), ACL injury (Loudon et al. 1996), and tibial stress syndrome (Simkin et al. 1989, Sommer et al. 1995). Foot structure and shape affect the comfort of the footwear (Hawes et al. 1994), often indicated as 'comfort fit' for the shoe. When studying the comfort of shoe inserts, the factors of structure and shape of the foot deserve consideration.

In shoe pressure and comfort

One of the import factors related to shoe comfort is the in-shoe pressure during human activities. The measurement of plantar pressure distribution has been widely used to characterize the functional aspects of foot-floor and foot-shoe interaction (Alexander 1990). Factors such as relative metatarsal length (Fox, 1950), the configuration of the medial longitudinal arch of the foot (Rodgers, 1995), and bony prominence (Duckworth, 1985) have all been implicated as leading to elevated plantar pressure. Since elevated peak plantar pressure has been shown to be associated with tissue damage to insensate feet (Boulton, 1983) and pain in rheumatoid arthritis (Lord, 1986), it is evident that good comfort of fit characteristics will mitigate against many common abrasion and pressure related foot conditions that often characterize the use of new shoes (Nigg, 1986). The plantar pressure distribution under the foot during functional activity has been shown to be related to insert comfort (Chen et al. 1994). However, a systematic study on the relation of plantar pressure distribution and insert comfort has not been done.

Foot sensitivity and comfort

The shoe insert may affect the comfort of the shoe through the interaction with the human foot sensory system. The importance of plantar mechanoreceptors has been demonstrated in many studies (Diener et al. 1984, Magnusson et al. 1990, Asai et al. 1992, Hamalainen et al. 1992). The effect of the receptors has been shown to vary with the interaction of standing surfaces (Watanable and Okubo 1981, Wu and Chiang 1996, Ingersoll and Armstrong 1992) and/or shoe inserts (Robbins et al. 1993, Chen et al. 1995). Robbins et al. (1993) found that the shapes and materials of shoe inserts influenced the balance of elderly men. Chen et al. (1995) showed that by changing sensory input to the feet, plantar pressure distribution changed significantly during gait. It is reasonable to speculate that the sensation of the plantar aspect of the foot may have an important effect on the comfort of the shoe insert.

METHODS

General procedure

A total of 106 male subjects volunteered in this project. The subjects ranged in age from 18 to 44 years old (average 23 years). Their shoe size ranged from US men's 8.5 to 11. Most subjects were classified as active with regular participation in athletic activities. Prior to testing, the procedure was explained and informed written consent was obtained from each of the subjects. Each subject was first asked to fill out a questionnaire to provide basic information about his physical condition and any injury or disease of his lower extremity. Only subjects without any current musculo-skeletal or lower extremity disorders were included in this study.

Measurements of foot shape, leg characteristics, and sensitivity were conducted on each subject. The details of these measurements are provided in the section of *foot and leg specific factors measured in this study* below.

Each subject was then asked to conduct walking and running trials on an indoor track while wearing the Combat Boot Mark III (Figure 1) provided by the Department of National Defense (DND). The army boots used for this study were available in the following sizes and mondopoints:

7.5-8	E	mondopoint 264/100
8.5	D	mondopoint 270/98
9-9.5	D	mondopoint 276/100
9-9.5	F	mondopoint 276/108
10-10.5	E	mondopoint 282/106
11	D	mondopoint 288/104
11	F	mondopoint 288/112

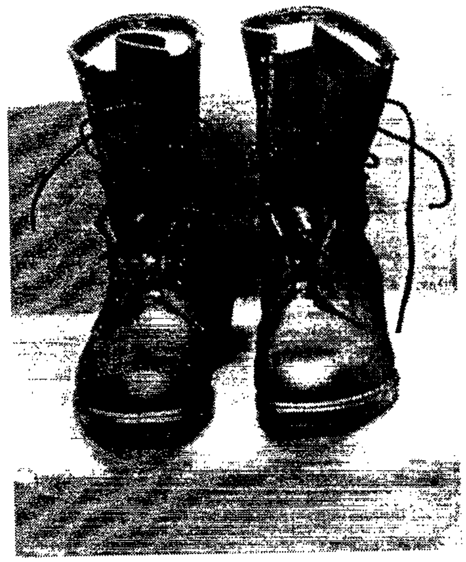


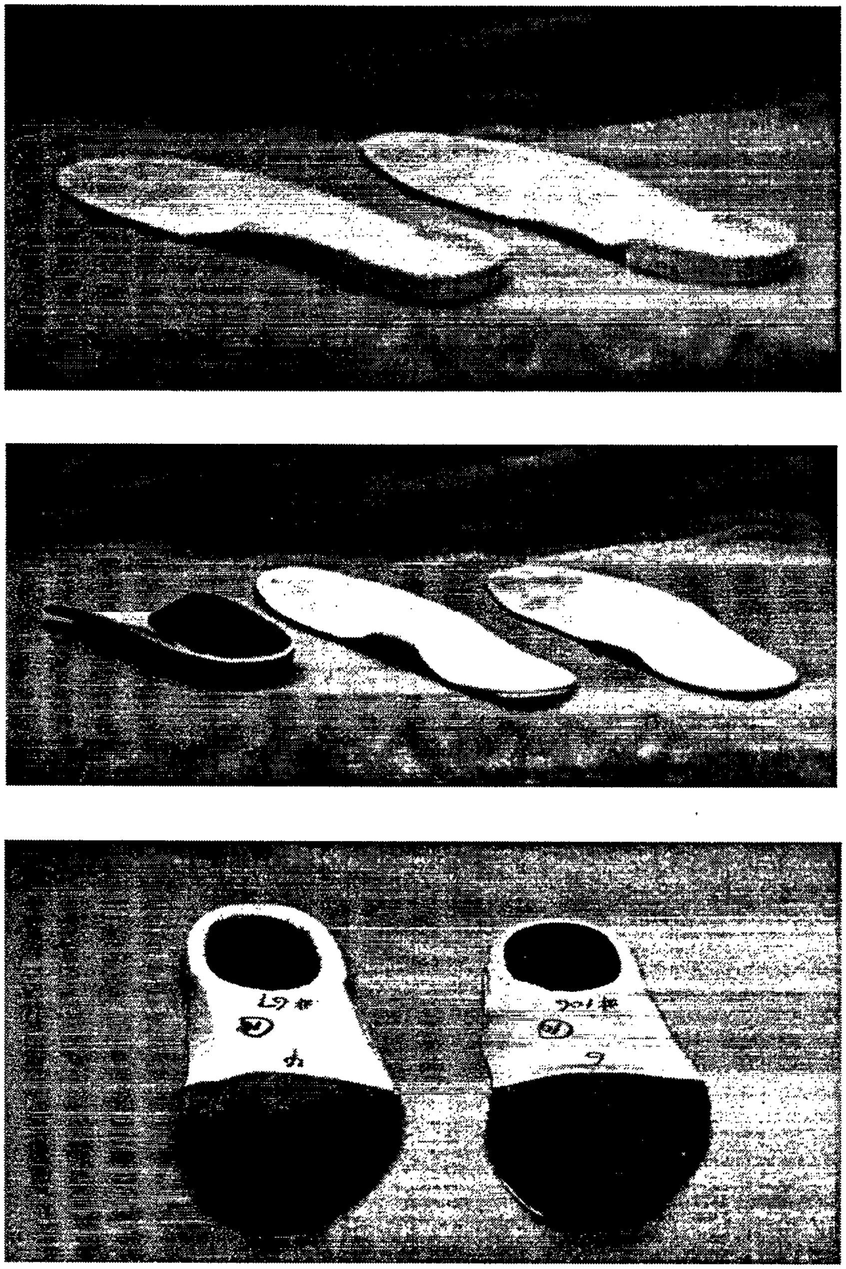
Figure 1. Photograph of a pair of the Combat Boot Mark III used in this investigation.

Each subject was instructed to chose the best fitting boots. Walking and running trials were conducted to subjectively evaluate the comfort of ten different shoe inserts. The details of the walking and running trials are provided in the section of *outcome criteria evaluated* below.

Ten different shoe inserts (Figure 2), provided by Schering-Plough (Dr. Scholl's) were used in this study. The inserts varied with respect to shape, hardness and viscosity. The specifications of these inserts are listed in Table 2.

Table 2. Specifications of the ten different inserts tested in this study.

No.	**Arch**	**Shape**	**Shape**	**Material**	**Material**	**Material**	**Elasticity**	**Elasticity**
		General	Heel	Heel	Medial Forefoot	Lateral Forefoot	Heel	Forefoot
1	High	Full	Spherical	Hard	Hard	Hard	Elastic	Elastic
2	High	Full	Spherical	Soft	Soft	Soft	Elastic	Elastic
3	High	Full	Spherical	Soft	Soft	Soft	Viscous	Viscous
4	High	Full	Spherical	Soft	Soft	Soft	Viscous	Elastic
5	Low	Full	Spherical	Soft	Soft	Soft	Viscous	Elastic
6	Low	Full	Flat	Hard	Soft	Hard	Elastic	Elastic
7	Low	Full	Flat	Hard	Hard	Soft	Elastic	Elastic
8	High	Full	Flat	Soft	Soft	Soft	Viscous	Elastic
9	High	Full	Flat	Soft	Soft	Soft	Elastic	Elastic
10	High	U-Shaped						



(a)

(b)

(c)

Figure 2. The inserts used in this investigation with different shapes as illustrated in: (a) two inserts with spherical heel but different arch height, (b) #10 insert with U-shape, and two inserts with flat heel but different arch height, and (c) #4 insert with viscous soft material at heel and #6 with hard elastic material at lateral forefoot and soft elastic material at medial forefoot.

The shoe and insert factors quantified in this study

S1 dimensions of selected inserts,
S2 internal boot dimensions,
S3 material properties of the inserts and
S4 sole hardness and flexibility.

Factor S1 ***Dimensions of selected inserts***

Arch height (H_{arch}) and heel cup height (H_{heel}) were measured as the highest point on the arch and heel cup of the inserts with respect to the centre of the heel, while the inserts were lying flat on a table (Figure 3).

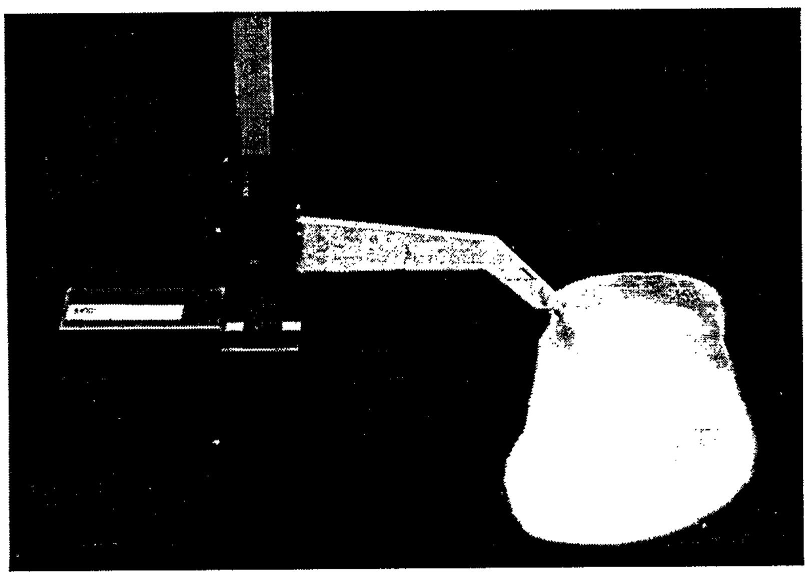


Figure 3. Photograph of the set up for the measurement of Arch height (H_{arch}) and heel cup height (H_{heel}) of each insert.

Factor S2 ***Internal boot dimensions***

The dimensions of the inside of each left boot were taken using an electro-magnetic digitizing device. The longitudinal axis was determined parallel to the two widest points on the medial side of the boot (Figure 4). The dorsum height of the boot was measured from the plantar surface of the boot to the inside of the upper, at the location of the top of the laces in the centre of the boot. The toe box height of the boot was measured at the edge of the toe cup, at the width of the centre of the first digit. Length and width measurements were made with respect to the most posterior and most medial parts of the boot plantar surface, respectively. The location of each digit on the boots was determined by taking the average width of each digit for all subjects who wore each boot. Subsequently, the lengths were measured. Heel breadth was measured as the internal boot width, 3 cm anterior to the end of the boot, at the plantar surface.

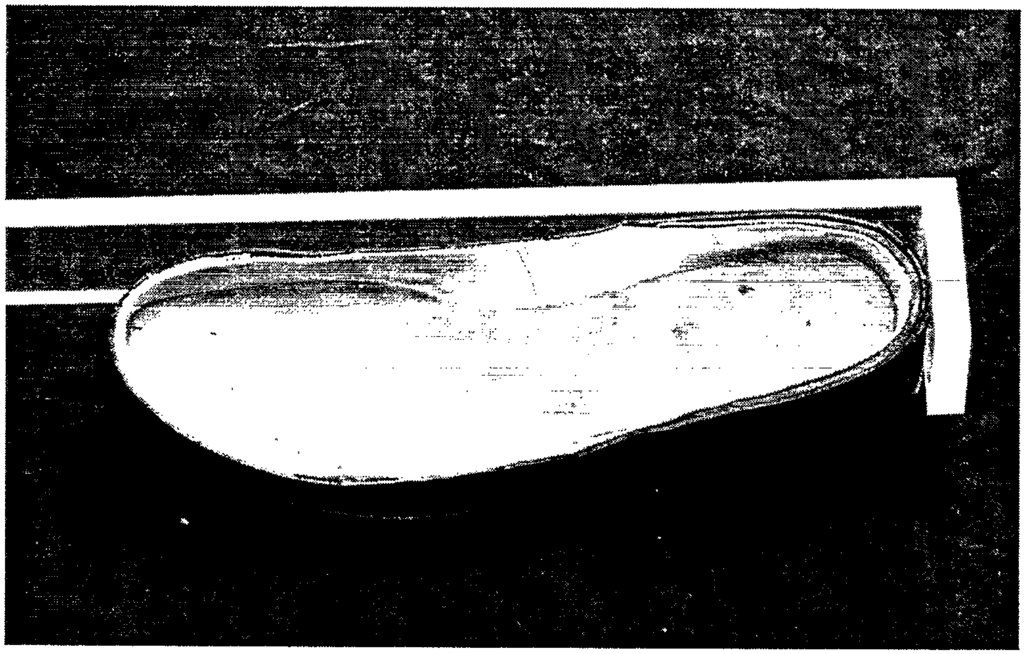


Figure 4. Photograph of the set up for the measurement of inside dimensions of each left boot.

Once the dimensions of the boot were measured, the variables determining the fit of the boot could be determined. These were calculated by taking the size of the boot variable minus the size of the respective foot variable for each subject (Table 3).

Table 3. Boot and insert variables

Variables	**Description**
ΔH_{hallux}	boot toe box height - foot hallux height
ΔH_{dorsum}	boot dorsum height - foot dorsum height
ΔL_{1T}	boot length of first toe - foot length of first toe
ΔL_{2T}	boot length of second toe - foot length of second toe
ΔW_{heel}	boot heel breadth - foot maximum heel breadth
$\Delta W_{forefoot}$	boot forefoot width - foot breadth measured from metatarsals

Factor S3 ***Material properties of the inserts***

The hardness and elasticity of the inserts were determined quantitatively. A motor was used to press a small cylinder of 0.5 cm^2 cross-sectional area into the insert, while a force transducer measured the corresponding force in volts (Figure 5). Deflection was determined by the number of turns of the motor. Data was collected in CODAS. The deflection of each insert material was measured from 0 to 400 kPa (maximum 20 N applied over 0.5 cm^2) during loading and unloading. Means and standard deviations of three trials were calculated. After removing part of the upper, the hardness and elasticity of the plantar surface of the boot could also be determined. Hardness and elasticity measurements were taken three times each at the centre of the heel, and means and standard deviations were calculated.

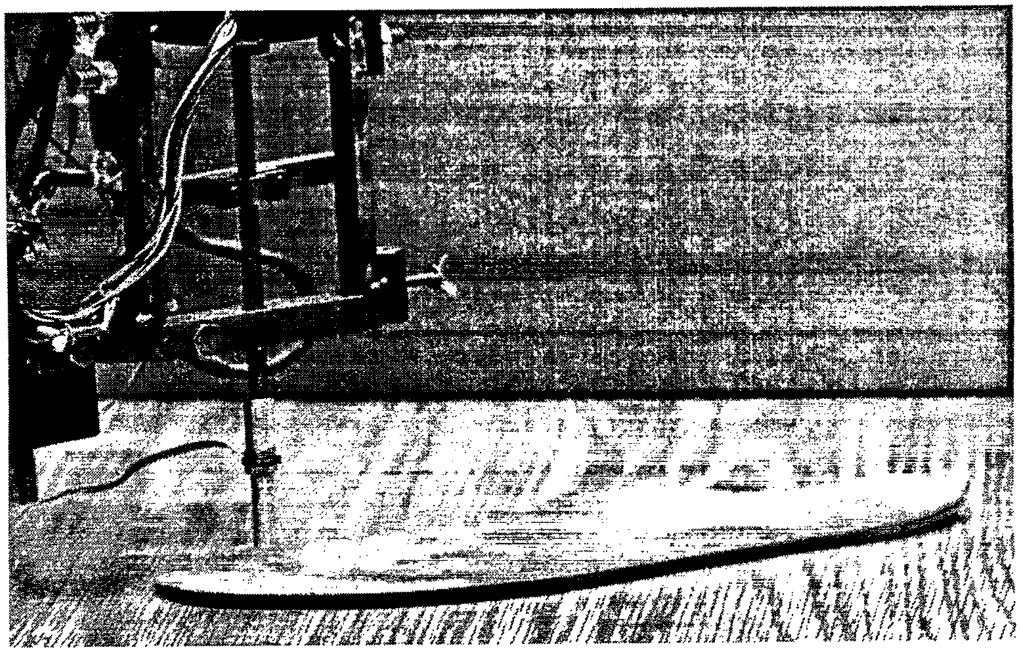


Figure 5. Photograph of the set up for the measurement of hardness of each insert.

Factor S4 ***Sole hardness and flexibility***

Using the same motor/transducer system, boot flexibility was measured by clamping the heel of the boot to a table while the boot was upside down, with the upper removed (Figure 6). The boot was supported by the table from the heel to a line between the widest part of the medial and lateral forefoot, which was assumed to be the flexion line. A downward force of 20 N was applied 5 cm anterior to the flexion line and the maximum vertical deflection of the boot was measured. Three trials were conducted and the means and standard deviations calculated.

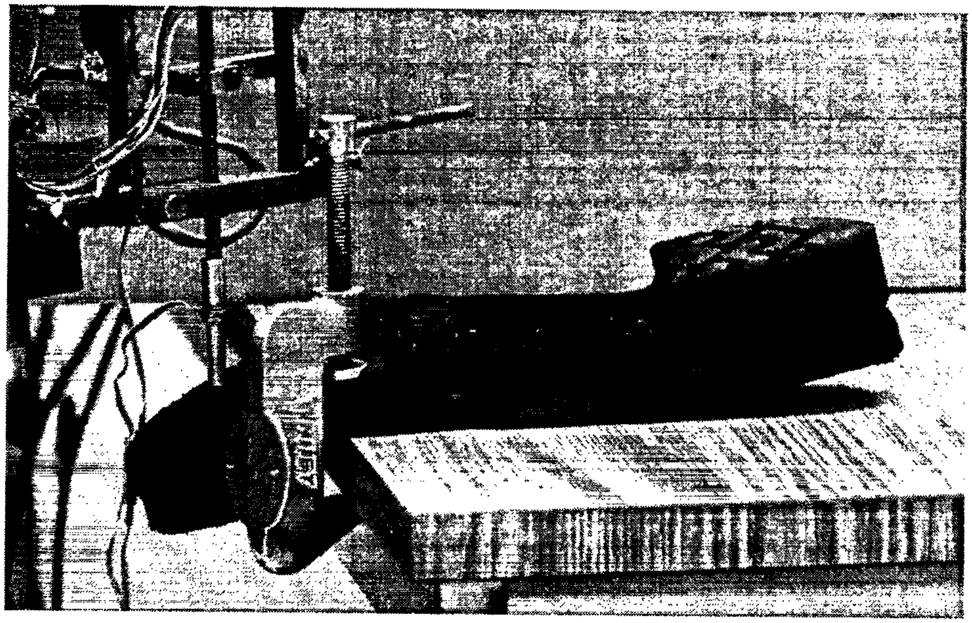


Figure 6. Photograph of the set up for the measurement of flexibility of the boot.

The foot and leg specific factors quantified in this study

F1 foot shape,
F2 foot arch (height, length),
F3 leg characteristics, and
F4 sensitivity of the plantar surface of the foot

Factors F1 – F3 Foot and leg characteristics

Foot shape, foot arch and leg characteristics (F1 - F3) were measured by digitization of the foot and leg. An electro-magnetic digitizing device (3Space fasttrak by Polhemus, Colchester, Vermont, USA) was used in the study (Figure 7). The device has a static accuracy of 0.7 mm for spatial position over a 76 × 76 × 76 cm cubic space. A transmitter fixed on the corner of a testing table emitted the magnetic field. A stylus with a precision tip is used to identify the point to be digitized. The stylus contained a receiver detecting the magnetic fields emitted by the transmitter. The testing table was a wooden board raised 44 cm above the floor to minimize the influence from any metal materials under the floor. There were no metallic materials on the table while digitization was conducted.

An anatomical reference frame was defined before any measurements could be taken on the foot (Figure 8). The X axis was a line formed by the projection onto the testing table of a plane which touched the edge of the medial aspect of the foot. The two contact points were close to the first metatarsal joint and center of the heel. The Y axis was a line formed by the projection onto the table of a plane perpendicular to the X axis, which touched the edge of the posterior aspect of the heel. The Z axis was a commonly perpendicular line to the X and Y axes starting from the table up. A jig consisting of two perpendicular plastic bars was built to help in the determination of the reference frame. Three small recess holes on the surface of the jig, as marked by o, x, and y (Figure 8), were digitized to establish a reference frame.

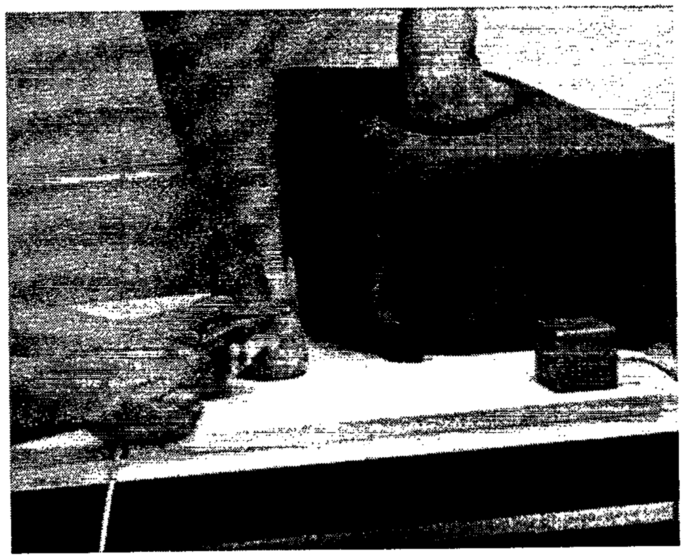


Figure 7. Photograph of the set up for digitization measurements on the left foot of a subject.

A total of 26 points on the surface of the foot and leg were selected for digitization (Table 4), as indicated on Figures 8, 9, and 10. From the digitized coordinates of the 26 points, a total of 23 variables were calculated to represent the characteristics of the shape, dimension and structure of the foot (Table 5). The variables included heights, lengths, widths and angles of the foot and leg. All height variables (depicted with a H) were measured as vertical distances from the testing table to the digitized points; all length variables (depicted with a L) were measured along the X axis; and all width variables (depicted with a W) were measured along the Y axis. Five angles were measured. The heel resting position angle, γ, was the angle measured in the YZ plane between a bisection line of the heel and the Z axis. The forefoot flexion angle, φ, was the angle enclosed by the Y axis and a line connecting the first metatarsal and fifth metatarsal joints. The angle of the heel to the tibia, β, was the angle between two bisection lines of the heel and the lower leg measured in the YZ plane. The tibia torsion angle, ξ, was the projected angle between a line connecting the two malleoli and a line connecting the tibial tubercle and the center point of the fibular head on the XY plane. The Q angle of the knee joint was the angle between a line connecting the tibial tubercle and the center of the patella, and a line connecting the center of the patella and the point of the anterior superior iliac spine (ASIS) projected onto the YZ plane. Except for the Q angle, which was measured during bipedal standing, all variables were measured during single leg support as the other leg rested on a platform to maintain balance (Robinson and Frederick, 1989). The five angles represented the structural characteristics of the lower extremities, which have been found to be correlated to sports injuries (Cavanagh 1980, Hamill et al. 1989, Messier et al. 1991).

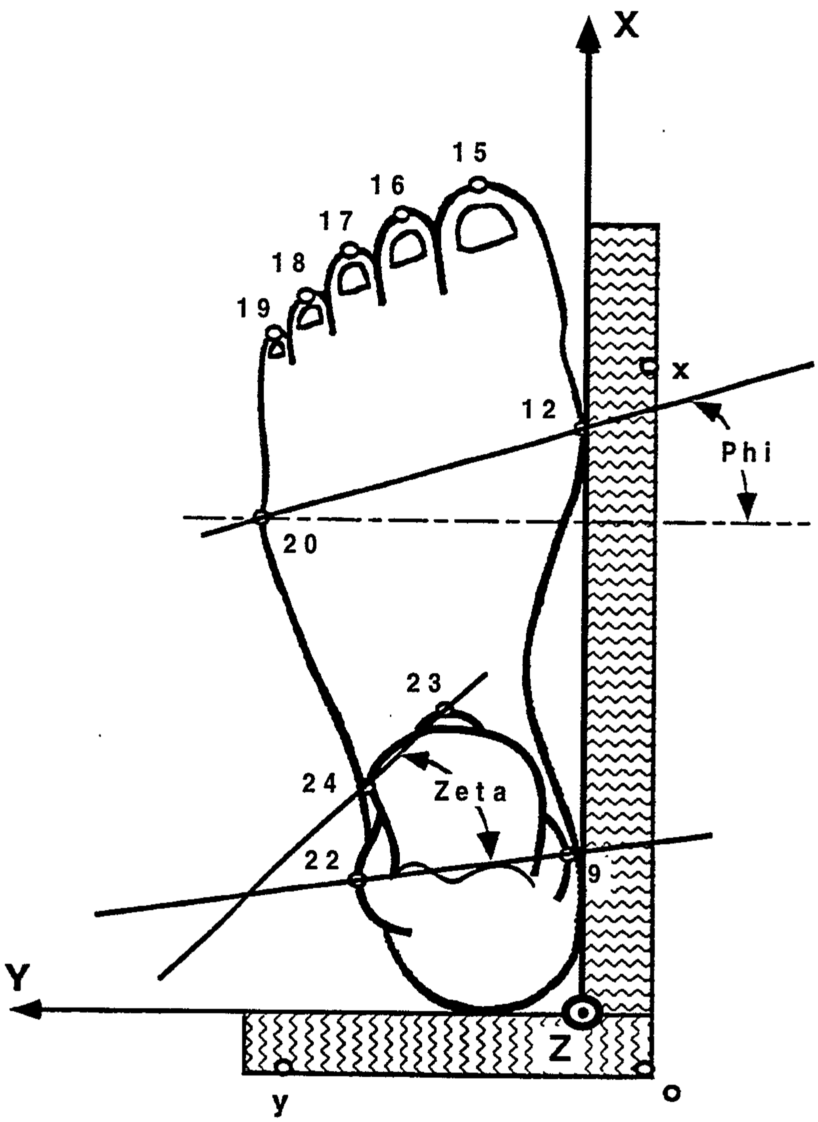


Figure 8. Superior view of a left foot with an anatomically defined reference frame. All marked points were the points for digitization.

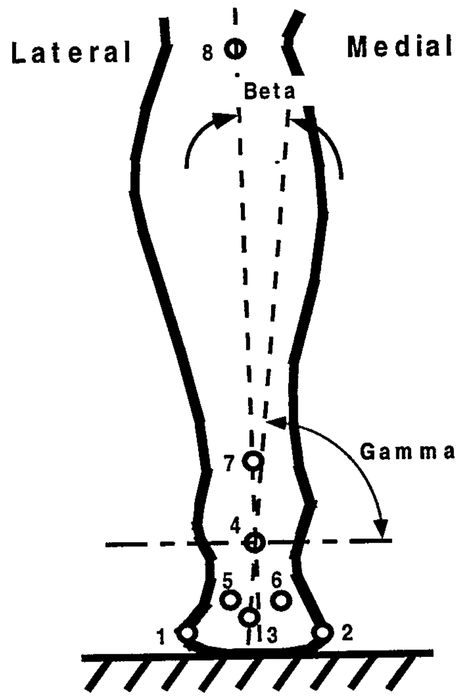


Figure 9. Posterior view of a left foot and leg with digitizing points marked.

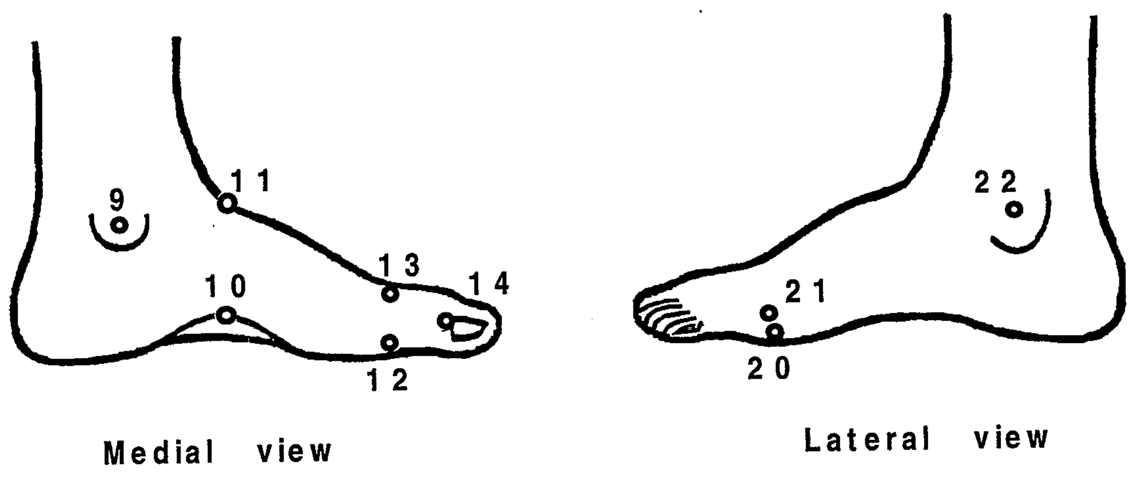


Figure 10. Medial view of a left foot with digitizing points marked.

Table 4. Definition and description of digitized points.

No.	Digitized point	Definition
1	lateral edge of heel	a point on medial heel, 2-3 mm above standing surface, about 3 cm anterior to the pternion
2	medial edge of heel	a point on lateral heel, 2-3 mm above standing surface, about 3 cm anterior to the pternion
3	distal posterior heel	a point on the bisection line of posterior calcaneus, 2-3 mm above standing surface
4	proximal posterior heel	a point on the bisection line of posterior calcaneus, about 4 cm above standing surface
5	lateral pternion	a point at lateral side representing maximum width of the calcaneus at pternion level
6	medial pternion	a point at medial side representing maximum width of the calcaneus at pternion level
7	distal bisection of leg	a point on the bisection line of posterior lower leg, and at the distal part of the lower leg
8	proximal bisection of leg	a point on the bisection line of posterior lower leg, and at the level of one third of the lower leg
9	medial malleolus	center point of medial malleolus
10	arch height point	intersection of a vertical frontal plane passing through talus head on the margin of the medial plantar curvature
11	dorsum height point	a point on the superior surface of the head of the talus
12	1st MH medial point	the most medially prominent point on the first metatarsal head
13	1st MH height point	the superior point of the first metatarsal head
14	hallux height point	a point on superior surface of the hallux
15	1st digit length point	the most prominent point on the first digit
16	2nd digit length point	the most prominent point on the second digit
17	3rd digit length point	the most prominent point on the third digit
18	4th digit length point	the most prominent point on the fourth digit
19	5th digit length point	the most prominent point on the fifth digit
20	5th MH lateral point	the most laterally prominent point on the 5th metatarsal head
21	5th MH height point	the superior point of the 5th metatarsal head
22	lateral malleolus	center point of lateral malleolus
23	tibial tuberocity	center point of tibial tuberocity
24	fibular head	center point of fibular head
25	patella center	center point of patella
26	ASIS point	center point of the anterior superior iliac spine (ASIS)

Table 5. Foot variables calculated from coordinates of digitized points.

Variables	Name	Calculated as
Height		
H_{hallux}	Hallux height	Z(14)
H_{1MH}	Height of the first metatarsal head	Z(13)
H_{5MH}	Height of the 5th metatarsal head	Z(21)
H_{dorsum}	Dorsum height	Z(11)
H_{arch}	Maximum arch height	Z(10)
H_{SF}	Sphyrion fibular height	Z(22)
H_{Pte}	Pternion height	Z(4)
Length		
L_{1T}	Length of heel to the first digit	X(15)
L_{2T}	Length of heel to the second digit	X(16)
L_{3T}	Length of heel to the third digit	X(17)
L_{4T}	Length of heel to the fourth digit	X(18)
L_{5T}	Length of heel to the fifth digit	X(19)
L_{1MH}	Length of heel to the 1st MH medial point	X(12)
L_{5MH}	Length of heel to the 5th MH lateral point	X(20)
L_{dorsum}	Length of heel to the dorsum	X(11)
Width		
W_{1T}	The distance from tip of the first digit to y axis	Y(15)
W_{2T}	The distance from tip of the second digit to y axis	Y(16)
W_{3T}	The distance from tip of the third digit to y axis	Y(17)
W_{4T}	The distance from tip of the fourth digit to y axis	Y(18)
W_{5T}	The distance from tip of the fifth digit to y axis	Y(19)
W_{heel}	Maximum heel breadth	Y(1) - Y(2)
W_{Pte}	Pternion heel breadth	Y(5) - Y(6)
$W_{forefoot}$	Foot breadth measured from first metetarsal to 5th metatarsal	Y(20) - Y(12)
Angle		
γ	Heel resting position angle during standing on one foot	*
φ	Fore foot flexion angle	**
β	Angle of heel to tibia during one foot standing	***
ξ	Tibia torsion angle during one foot standing	****
Q	Q angle of knee joint	*****

* This angle was the angle measured in XZ plane between a line connecting point 3 and 4 and the horizontal line.

** This angle was the angle measured in XY plane between a line connecting point 12 and 20 and X axis.

*** This angle was the angle measured in XZ plane between a line connecting point 3 and 4 and a line connecting point 7 and 8.

**** This angle was the angle measured in XY plane between a line connecting point 9 and 22 and a line connecting point 23 and 24

***** This was the angle measured in XZ plane between a line connecting point 23 and 25 and a line connecting point 25 and 26.

A computer program was developed to perform the calculation of all parameters. The program first established a coordinate system from the coordinates of the three digitized points (o, x, and y) and then shifted the reference frame by compensating the offsets of this coordinate system along its three axes. The coordinates of all digitized points were then converted to the reference frame from a global frame attached on the transmitter of the digitizing device. Finally, the program computed all parameters from the coordinates of the digitized points.

Factor F4 Foot sensitivity

The sensitivity of the plantar surface of the foot was evaluated by a touch pressure threshold test and by a vibration threshold test. Touch pressure thresholds were determined using Semmes-Weinstein monofilaments (North Coast Medical, Inc.) (Figures 11 and 12). Each filament had a specified diameter and a known buckling force. The filaments were numbered such that each number represents its buckling force and is equal to log (10 * buckling force (mg)). A set of filaments, which contained the 1.65, 2.36, 2.83, 3.61, 4.08, 4.31, 4.56, 5.07 and 6.65 monofilaments, was used in this study. During the test, the subject lied down on his back in a quiet room with a curtain preventing any view of his foot and the examiner. The examiner controlled a light seen by the subject and the touch stimulus was applied only when the light was on. The light was an indication for the subject to concentrate and respond whether or not a pressure sensation was felt in the area of the foot being tested. A modified 4, 2, 1 stepping algorithm (Dyck et al., 1993) was used to determine the pressure threshold at five locations on the left foot of each subject (heel, medial arch, first metatarsal head, fifth metatarsal head and hallux).

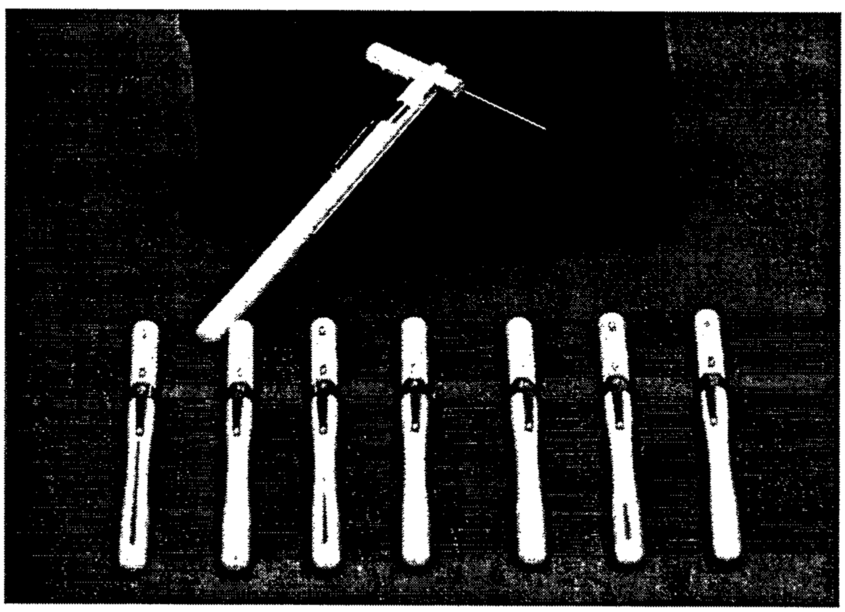


Figure 11. Photograph of the set of monofilaments (foot kit) used in this investigation.

Vibration thresholds were determined using a vibration exciter (Bruel and Kjaer, type 4809) powered by an oscillator (Bruel and Kjaer, type 1022) with variable amplitude and frequency of vibration (Figure 13). A metal probe 8 mm in diameter was screwed into the vibration exciter and fed through a wooden foot rest. The steel probe had a flat surface with rounded edges. The diameter of the hole in the foot rest was 13 mm, and the probe protruded 1.5 mm from the board.

An accelerometer (Bruel and Kjaer, type 4367) was mounted beside the metal probe on the exciter and attached to a RMS multimeter (Fluke 8060A) through a signal conditioner. The use of an accelerometer allowed for accurate measurement of the probe's movement, and compensated for the various damping effects of different locations on the foot. Each subject's left foot was tested at three locations: the heel, first metatarsal head and hallux. The test was performed using a method of increasing and decreasing amplitude at 125 Hz (Peripheral Neuropathy Association, 1993). The amplitude was increased until the subject reported feeling the vibration stimulus - the vibration perception threshold (VPT). The amplitude was then immediately decreased until the subject reported that he could no longer feel the stimulus - the vibration disappearance threshold (VDT). This was repeated in succession five times so that a total of ten measurements were obtained. The vibration threshold was calculated by removing the highest and lowest VPT's and VDT's, and averaging the remaining six values. The accelerometer was calibrated to the displacement such that 1 g = 2.2 V from the multimeter. Results were then integrated to obtain displacement.

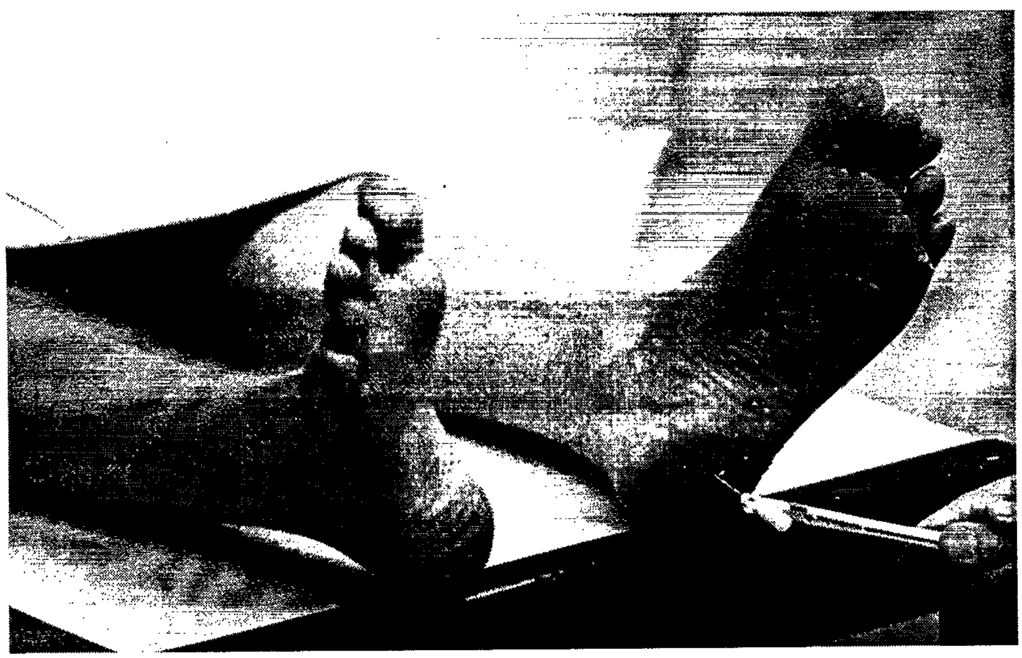


Figure 12. Photograph of the set up of touch sensitivity measurement.

The following sensitivity variables were analyzed in this investigation:

Tactile (touch pressure)

T_{heel}	tactile threshold at the heel: threshold filament number
T_{march}	tactile threshold at the medial arch: threshold filament number
T_{hallux}	tactile threshold at the hallux: threshold filament number
T_{mh1}	tactile threshold at the first metatarsal head: threshold filament number
T_{mh5}	tactile threshold at the fifth metatarsal head: threshold filament number

Vibration

V_{heel}	vibration threshold at the heel
V_{hallux}	vibration threshold at the hallux
V_{mh1}	vibration threshold at the first metatarsal head

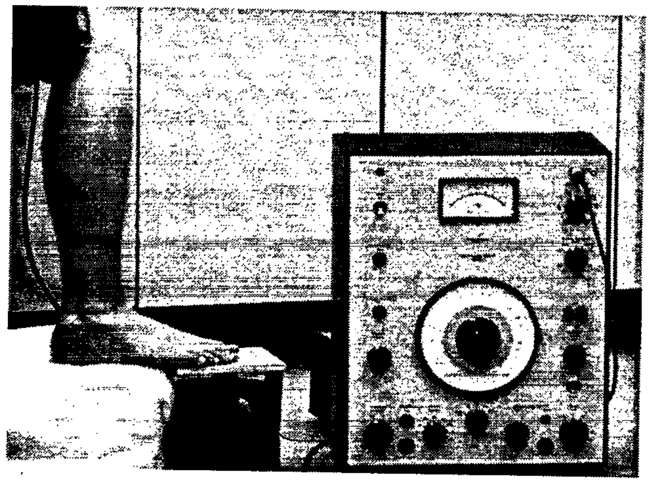


Figure 13. Photograph of the set up of vibration sensitivity measurement.

The outcome criteria evaluated

C1 subjective general short-term (fit) comfort during standing, walking and running,
C2 subjective pain or discomfort during the described conditions,
C3 in-shoe pressure distribution between the plantar surface of the foot and the superior of the insole, during walking.

Criteria C1 Subjective comfort

The subjective short-term comfort of each insert was evaluated during walking and running on an indoor track. After placing the insert in the army boots, the subject rated the insert from 1 to 10 after walking for about 200 meters. He then ran for about 200 meters and rated the insert again from 1 to 10 based on comfort. This procedure was repeated by the subject until he finished the evaluation trials for all ten inserts. A rating of 10 was the most comfortable and 1 was the least comfortable. The order in which the ten inserts were evaluated was randomly selected without the subject's awareness. Each subject walked and ran at their preferred speed during each trial.

In order to test the repeatability of the subjective comfort rating, each subject actually evaluated 11 inserts (ten inserts plus one which was repeated). Thus, each of the ten inserts were repeatedly evaluated by at least ten subjects. The order of the repeated insert within the ten tested inserts was randomly selected without the subject's awareness.

A paired t-test was used to compare the repeatability of subjective comfort ratings. A multiple analysis of variance (MANOVA) test was used to determine the significance level of the variance of subject comfort ratings for ten different inserts over two conditions. A post-hoc test using Student-Newman-Keuls test was conducted to identify the significant differences between different shoe inserts.

Criteria C2 ***Subjective pain***

Each subject was asked to record comments of pain or discomfort that he experienced during walking and/or running while wearing the boots with each insert.

Criteria C3 ***Pressure distribution***

The in-shoe pressure distribution between the plantar surface of the foot and the superior of the insole during walking was recorded for ten subjects randomly selected from all tested subjects. For analysis the foot was divided into five sections representing the heel, medial arch, lateral arch, metatarsal heads and toes (Figure 14). The peak pressures at these five sections were determined from recorded raw data for each footfall. An in-shoe pressure insole system (F-Scan, Tekscan, Inc. Boston, Mass) with sensors measuring 0.25 cm^2 (0.2 in by 0.2 in) was used to collect the pressure distribution data (Figure 15). The insole transducer was cut to the appropriate size and then inserted into the left boot on top of the insert. The subject wore the boots with the insole transducer inside and walked five steps at his preferred speed. The speed was monitored to ensure consistency across the different inserts tested. During walking, the pressure under the left foot was measured at a sampling frequency of 50 Hz. The same procedure was repeated for all ten inserts in a randomized order. The reported peak pressure values are the average of the peak pressure over the middle three footfalls.

The following pressure variables were analyzed in this investigation:

P_{heel}	heel peak pressure: maximal pressure under the heel during stance phase.
P_{March}	medial arch pressure: maximal pressure under the medial arch during stance phase.
P_{Larch}	lateral arch pressure: maximal pressure under the lateral arch during stance phase.
P_{MH}	metatarsal heads pressure: maximal pressure under the metatarsal heads during stance phase.
P_{toes}	toes pressure: maximal pressure under the toes during stance phase.
d_{COP}	range of center of pressure pattern in the medio-lateral direction: the difference between the maximal and the minimal position of the center of pressure in the medio-lateral direction.

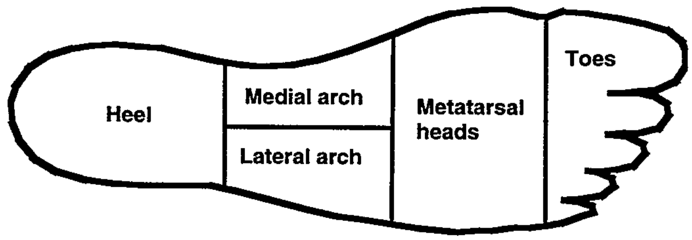


Figure 14. The five areas of plantar aspect of the foot where the peak pressures were measured using F-Scan in-shoe pressure measurement system.

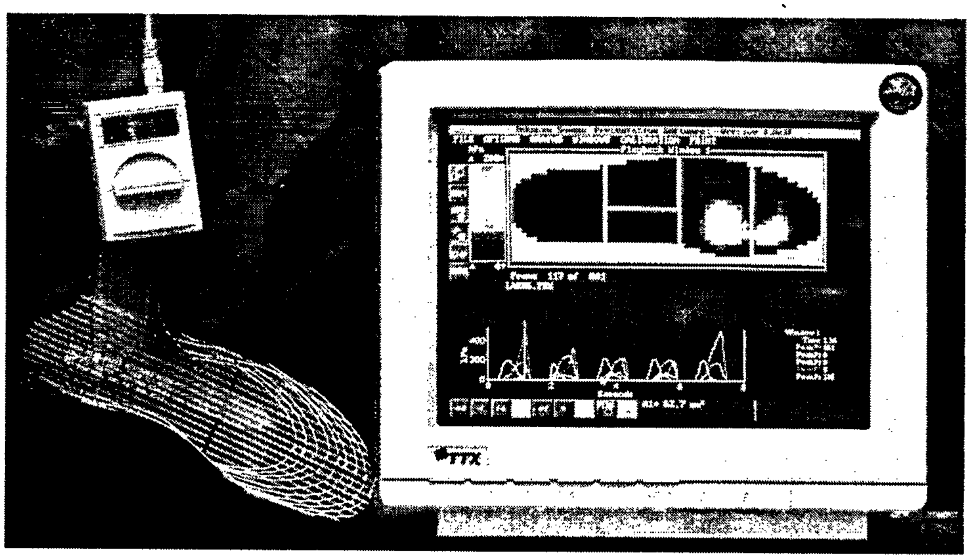


Figure 15. Photograph of the F-Scan in-shoe pressure measurement system used in this investigation.

Relationship Between Foot Sensitivity and Plantar Pressure

An additional side study was conducted in an attempt to determine a relationship between foot sensitivity and plantar pressure distribution. Fifteen subjects, eleven males and four females, were recruited from the University of Calgary for this experiment (age: 26.2 ± 6.28 yrs; height: 173.3 ± 4.76 cm; weight: 74.25 ± 7.91 kg). All subjects were free of any known neurological dysfunction or disease that might impair their performance in this test.

Similar to the methods already mentioned, two types of sensitivity tests were administered, a pressure threshold and a vibration threshold test. Plantar pressure distributions were measured using Pedar flexible insoles (Novel, Inc.). The insoles were held against the subjects' left foot using nylon stockings. The stockings were wrapped with a thin flexible material to prevent slippage during the trials. Timing lights ensured consistent walking speeds of 1.5 $ms^{-1}$and running speeds of 3.5 ms^{-1} within a tolerated range of ±10%. During walking trials, the pressures under the left foot were measured at a sampling rate of 99 Hz. While running, the subjects left rearfoot and forefoot were independently measured at 189 Hz. Five trials were recorded for each condition to obtain a minimum of five footfalls for pressure measurements. Peak pressures were determined by averaging the peak pressures found at the heel, medial and lateral arches, metatarsal heads and the hallux for each of the five footfalls.

All data were analyzed using SPSS statistical software (SPSS Inc., Chicago, Ill.). Nonparametric pressure data from the filament trials was analyzed using Friedman ANOVA and Wilcoxon signed rank tests. Parametric data was analyzed using multivariate ANOVA tests. A correlation matrix of all variables was created to determine the significance of any linear relationships. Stepwise linear regression analysis was performed on location matched variables with the sensitivity measurements as the independent variables and the plantar pressures as the dependent variables. The level of significance was set a priori at $p<0.05$.

RESULTS AND DISCUSSION

The shoe and insert factors

Factor S1 ***Dimensions of selected inserts***

The various dimensions of the inserts used in the study are presented in Table 6. The average values and standard deviations of three trials are presented. The arch height in the high-arched inserts was approximately 9mm higher than in the low-arched inserts. The arch height of insert #10 was almost 4mm higher than the high-arched inserts. The highest point of the spherical heel was over 11mm higher than the flat insert. The thickness of the flat regions of the inserts (forefoot and flat heel) was between 2 and 2½mm.

Table 6. Arch heights and heel heights of the different inserts included in this study (mean and standard deviation of three measurements).

Dimensions	**Height [mm]**
high arch	17.40 (4.76)
low arch	8.69 (1.43)
Insert 10 arch	21.20 (0.41)
Spherical heel	13.47 (1.14)
flat heel	2.34 (0.54)

Factor S2 ***Internal boot dimensions***

The digitized internal boot dimensions are shown in Table 7. Values are provided for each boot size that was included in the investigation. The average and standard deviation of three measurements are presented. As can be seen from the data, not all of the boot dimensions are scaled symmetrically.

Table 7. Internal boot dimensions including heights (H), widths (W) and lengths of the different boot sizes used in this investigation. Values given are the mean and standard deviations of three trials.

Dimensions	**Size 8 1/2D [mm]**	**Size 9F [mm]**	**Size 10E [mm]**	**Size 11E [mm]**
H_{hallux}	33.38 (0.26)	39.38 (0.47)	39.89 (1.10)	40.29 (0.31)
H_{dorsum}	67.95 (0.90)	69.34 (0.60)	70.94 (0.74)	81.20 (0.85)
L_{1T}	273.89 (0.42)	282.10 (0.18)	283.60 (0.41)	293.40 (0.69)
L_{2T}	272.82 (0.27)	282.62 (0.30)	288.16 (0.42)	291.75 (0.05)
L_{3T}	257.23 (1.56)	272.43 (0.50)	275.85 (0.52)	281.14 (0.15)
L_{4T}	240.34 (0.17)	247.18 (0.45)	262.77 (0.38)	266.01 (0.19)
L_{5T}	217.14 (0.24)	229.33 (0.27)	247.67 (0.15)	246.64 (0.26)
L_{1MH}	194.55 (0.19)	196.13 (0.24)	197.57 (0.61)	193.50 (6.48)
L_{5MH}	182.67 (0.62)	179.78 (0.41)	186.64 (0.35)	194.60 (0.95)
$W_{forefoot}$	89.21 (0.50)	97.93 (0.40)	98.07 (0.42)	98.20 (0.14)
W_{heel}	59.66 (0.57)	66.33 (0.75)	59.91 (0.61)	61.64 (0.43)

Factor S3 ***Material properties of the inserts***

The midfoot region, which was consistent for all of the inserts, had the softest material (Table 8). In order of increasing hardness were the soft elastic, viscous and hard elastic materials. The heel material of insert #10 was relatively soft exhibiting the lowest hardness when tested with the force-deformation method and the second lowest Shore C value of the different materials.

Table 8. Insert hardness quantified using typical force-deformation and Shore C indentation measurements (mean and standard deviation of three trials.)

Insert material	**Hardness [kPa/mm]**	**Hardness Shore C**
hard elastic	256.61 (8.30)	65.3 (2.5)
soft elastic	102.32 (9.73)	39.3 (4.2)
midfoot material	88.35 (0.71)	30.0 (1.0)
insert 10 heel	76.70 (2.06)	37.0 (1.0)
viscous	142.60 (11.42)	49.3 (2.5)

Factor S4 ***Sole hardness and flexibility***

The material properties of the army boot midsole that were measured in this investigation included the sole hardness and flexibility. The hardness of the midsole was 3275.2 ± 564.9 kPa/mm. Thus, the hardness of the boot midsole is considerably higher than the hardest insole. The standard deviation of this measurement is also much higher due to small movements of the boot during testing.

The midsole flexibility of the army boots is calculated in terms of the deflection of the boot under a load of approximately 20N. The flexibility was determined to be 1.43 ± 0.06 degrees/Nm. This is very stiff compared to typical running shoes which generally have values on the order of 3 degrees/Nm.

Measured foot and leg specific factors

Factors F1 - F3 Foot and leg characteristics

The measured foot shape and dimension parameters are shown in Table 9 and Table 10. Large variations in most of the parameters were found among the tested subjects. The average fit of the boots is shown in Table 11. A smaller difference between the boot and the foot corresponds to a tighter fit. In general, the boots fit biggest at the toe box (ΔH_{hallux}), and tightest across the dorsum. This is an agreement with comments received from many of the subjects, who complained that the boot was too tight across the dorsum of their foot. Overall, there was about 10 to 15 mm space in the length of the boot, however, the width was generally tighter (0.18 to -2.29 mm).

Table 9. Minimum, maximum and average (mean and standard deviation) alignment angles of the feet and lower legs of the 106 subjects included in this investigation

Angle	Average [deg]	Minimum [deg]	Maximum [deg]
γ	2.80 (1.98)	0.06	7.14
φ	19.47 (2.91)	9.05	26.04
β	6.97 (3.33)	0.76	15.01
ξ	26.75 (7.80)	9.94	43.15
Q	14.62 (5.42)	5.05	27.27

Table 10. Minimum, maximum and average foot dimensions including heights (H), widths (W) and lengths of the 106 subjects measured in this investigation.

Variable	Average [mm]	Minimum [mm]	Maximum [mm]
H_{arch}	28.53 (4.55)	13.78	39.39
H_{hallux}	18.08 (3.04)	13.01	32.27
H_{1MH}	35.36 (3.02)	27.94	45.03
H_{5MH}	19.40 (3.70)	12.46	26.93
H_{dorsum}	78.53 (5.65)	63.55	93.35
H_{SF}	66.47 (7.27)	47.73	80.87
H_{Pte}	54.58 (4.24)	44.58	69.42
L_{1T}	271.18 (8.76)	253.03	293.35
L_{2T}	264.57 (9.55)	244.06	285.61
L_{3T}	253.09 (9.94)	231.27	274.31
L_{4T}	237.06 (9.63)	215.71	257.72
L_{5T}	215.99 (8.18)	195.75	233.81
L_{1MH}	200.81 (5.96)	188.21	214.46
L_{5MH}	165.90 (6.61)	148.06	179.50
L_{dorsum}	109.45 (5.42)	96.64	121.37
W_{1T}	27.55 (7.55)	18.89	41.91
W_{2T}	54.43 (8.43)	29.56	70.92
W_{3T}	70.69 (8.25)	48.59	86.07
W_{4T}	83.84 (7.58)	63.54	100.17
W_{5T}	95.02 (6.81)	74.54	110.14
W_{heel}	63.39 (3.84)	53.57	71.55
W_{Pte}	31.10 (3.43)	20.91	39.91
$W_{forefoot}$	98.65 (4.74)	81.77	109.88

Table 11. Tightness of fit variables where the dimension of the foot was subtracted from the dimension of the boot. Positive values indicate that the boot was larger than the foot while negative values indicate the foot was larger than the boot.

Variable	Average [mm]	Minimum [mm]	Maximum [mm]
ΔH_{hallux}	20.53 (3.36)	9.18	26.55
ΔH_{dorsum}	-8.94 (5.71)	-24.01	5.79
ΔL_{1T}	9.89 (7.96)	-11.25	26.05
ΔL_{2T}	16.52 (8.71)	-0.13	38.56
ΔL_{3T}	10.65 (9.06)	-10.32	28.50
ΔL_{4T}	12.66 (9.54)	-8.23	31.47
ΔL_{5T}	15.51 (10.38)	-4.48	36.53
ΔL_{1MH}	-4.67 (5.71)	-17.25	6.90
ΔL_{5MH}	15.58 (6.74)	-1.12	31.72
ΔW_{heel}	0.18 (5.37)	-10.24	12.76
$\Delta W_{forefoot}$	-2.29 (5.33)	-17.76	16.16

Factor F4 Foot sensitivity

The distribution of the monofilament thresholds at the five locations of the foot (Figure 16) showed different patterns. At the medial arch more than two thirds of the subjects had their monofilament threshold at the 3.61 level with the rest of the subjects at a threshold lower than 3.61. At the 1st metatarsal head more than two thirds of the subjects had their monofilament threshold at the 3.61 level with almost all of the other subjects at a threshold higher than 3.61. At the heel, the 5th metatarsal head and the hallux, quite a number of subjects had their monofilament threshold at levels at or higher than 3.61, especially at the heel (52% of the subjects had thresholds at or higher than 3.61).

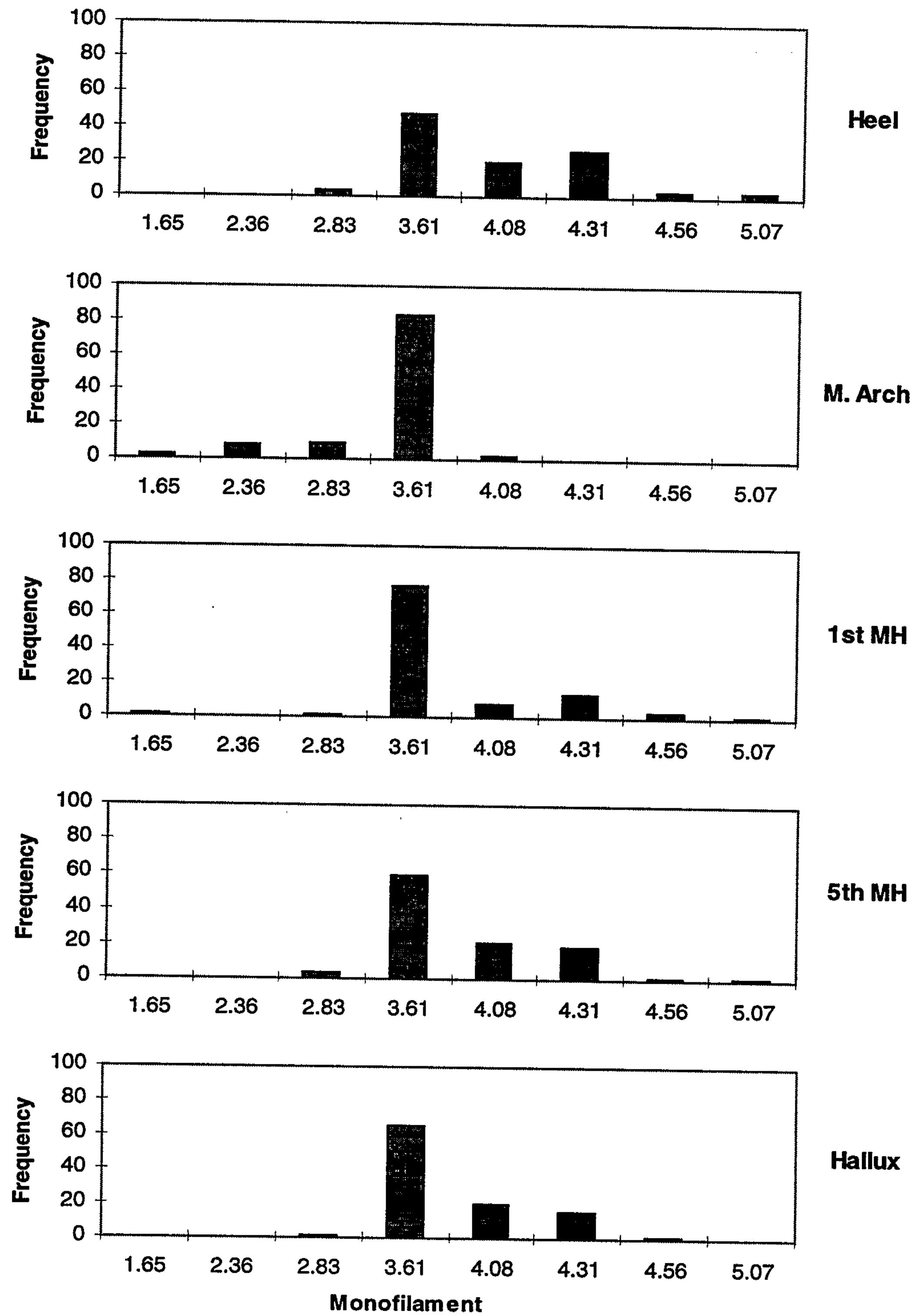


Figure 16. Distribution of monofilament thresholds at five different locations of the left feet of 106 subjects tested.

An analysis using Wilcoxon Matched-Pairs Signed-Ranks test of the various locations showed significant differences in the monofilament thresholds. The medial arch was significantly more sensitive than the heel, the 1st metatarsal head, the 5th metatarsal head and the hallux (Table 12). The heel was significantly less sensitive than the other locations of the foot. Three locations tested, i.e. the 1st metatarsal head, the 5th metatarsal head and the hallux had no significant difference in their monofilament threshold.

Table 12. The two tailed p-values from a Wilcoxon Matched-Pairs Signed-Ranks test to compare monofilament threshold levels at various locations on the foot. Significant differences are shown in bold font.

	Heel	M. Arch	1st MH	5th MH	Hallux
Heel	-	**<0.001**	**<0.001**	**0.047**	**0.003**
M. Arch	**<0.001**	-	**<0.001**	**<0.001**	**<0.001**
1st MH	**<0.001**	**<0.001**	-	0.059	0.283
5th MH	**0.047**	**<0.001**	0.059	-	0.546
Hallux	**0.003**	**<0.001**	0.283	0.546	-

A three-group cluster analysis of monofilament thresholds for all locations of the foot resulted in three subsets of subjects (Figure 17). The three subsets of subjects were classified as less sensitive, medium sensitive and more sensitive subjects according to their sensitivity thresholds. There were 25, 64 and 17 subjects included in the less sensitive, medium sensitive and more sensitive groups, respectively. The less sensitive group were generally less sensitive at the heel, the 1st metatarsal and the hallux. The subjects in the more sensitive group were generally more sensitive at the medial arch.

The distribution of the vibration thresholds at the three different locations of the foot showed different patterns (Figure 18). At the 1st metatarsal head, most of the subjects had their vibration threshold values less than 2 µm. However, the vibration threshold values were widely spread out at levels higher than 2 µm at the heel and the hallux.

An analysis of variance test (ANOVA) of different locations of the foot showed a significant difference in vibration thresholds ($P<0.001$) among the three locations tested (Figure 19). This difference could be the result of different loading conditions over long periods of time. The differences may have an influence on the control of locomotion which should be quantified in future studies.

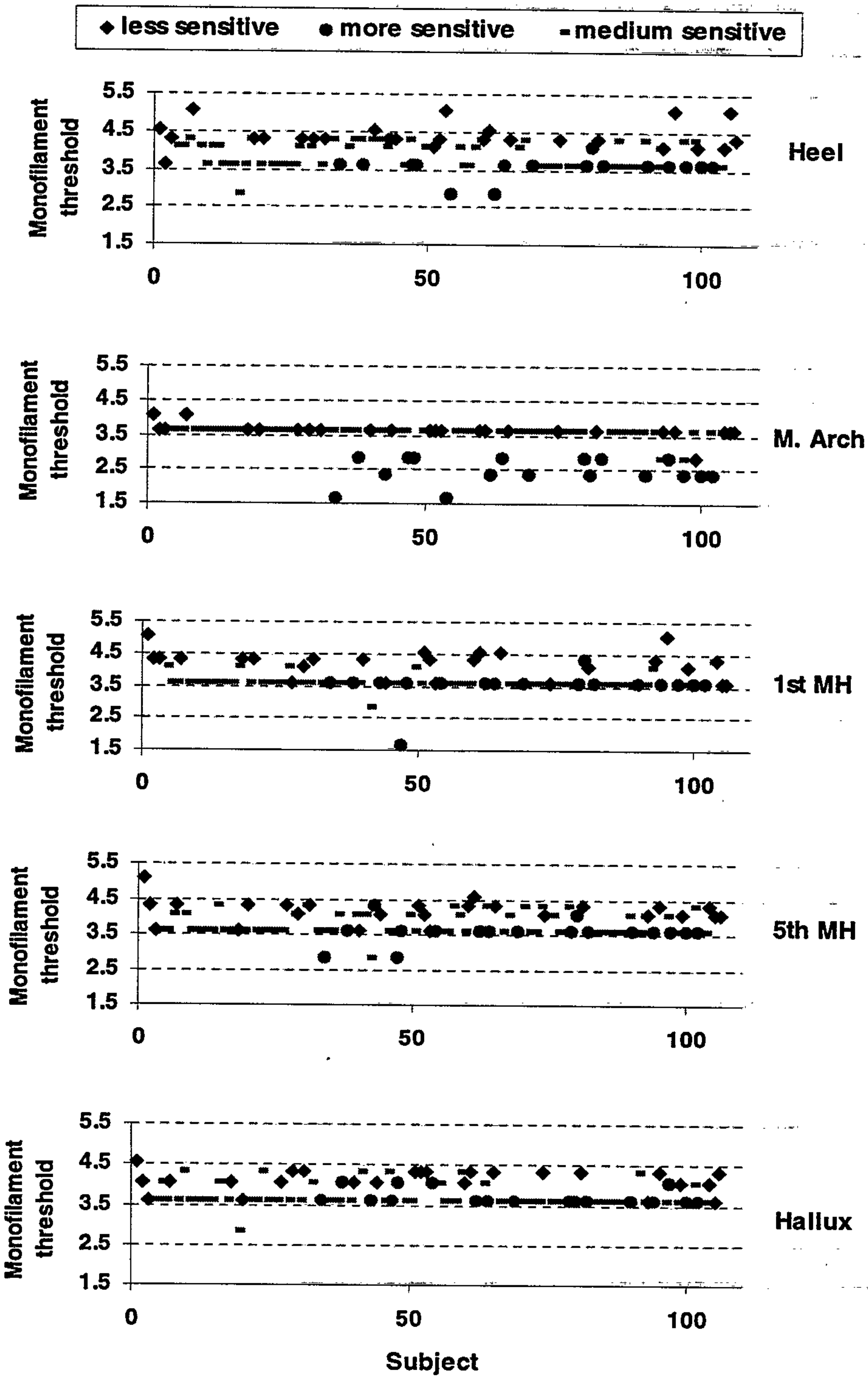


Figure 17. Three group cluster of monofilament threshold at five locations tested on the feet of 106 subjects.

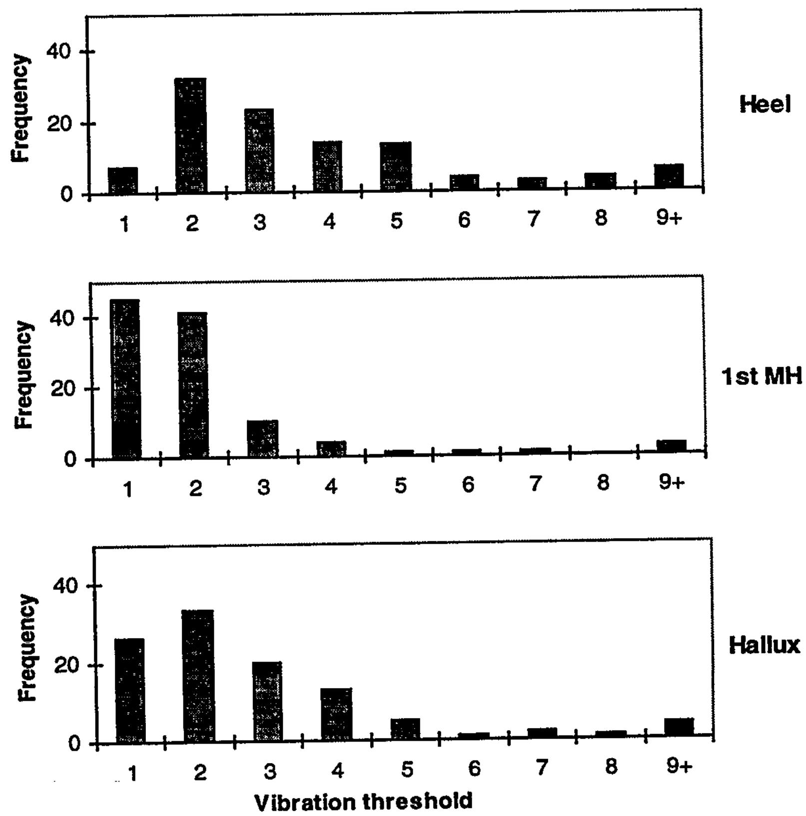


Figure 18. Distribution of vibration threshold at three different locations of the left feet of 106 tested subjects. The vibration threshold was divided into nine intervals with 1 representing the threshold value within 0-1 µm, and so on. 9+ represents all threshold values bigger than 8 µm.

There were significant correlations between monofilament threshold and vibration threshold at the same locations tested on the foot in this study (Table 13). Although the correlation was significant, the small values of correlation coefficients indicated that the correlation was rather weak between the two types of foot sensation.

Table 13. Correlation coefficients between monofilament threshold and vibration threshold at three locations on the foot. Significant correlations at the $P<0.05$ level are shown in bold font.

	Monofilament threshold		
Vibration threshold	Heel	1st MH	Hallux
Heel	**0.410**		
1st MH		**0.406**	
Hallux			**0.304**

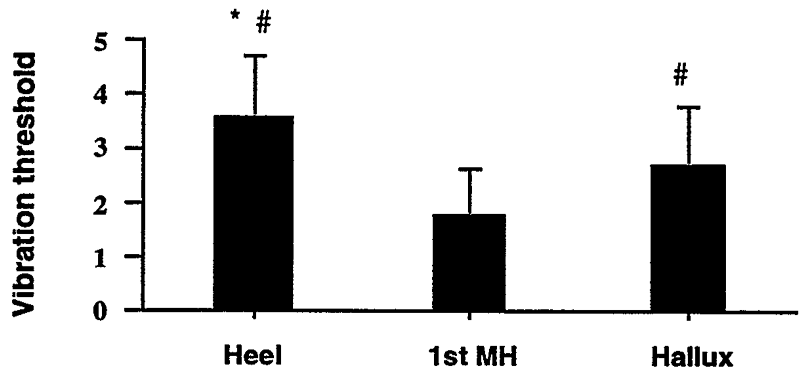


Figure 19. The mean and standard error of vibration threshold at three locations of the left feet of 106 subjects tested. The symbol (*) indicates significant higher vibration threshold than hallux. The symbol (#) indicates significant higher vibration threshold than 1st metatarsal head (MH).

Outcome criteria

Criteria C1 *Subjective comfort*

Repeatability

The difference in the mean value of comfort rating between two repeated tests on the same insert was 0.103 for walking, and 0.008 for running. A paired t-test showed no significant difference in mean values of comfort rating in two repeated tests under walking (P=0.693) and running (P=0.422) conditions. The correlation coefficient (R) for repeated tests was 0.51 for walking and 0.59 for running.

Distribution of comfort ratings

Comfort ratings were generally close to normally distributed for all shoe inserts evaluated in this study (Figures 20 and 21). The differences between the inserts were what comfort rating the distribution was centered around. Insert #10 had two peaks at comfort ratings of 1 and 5. This indicated that one group of subjects found the insert to be extremely uncomfortable while another group of subjects found the insert to be of average comfort.

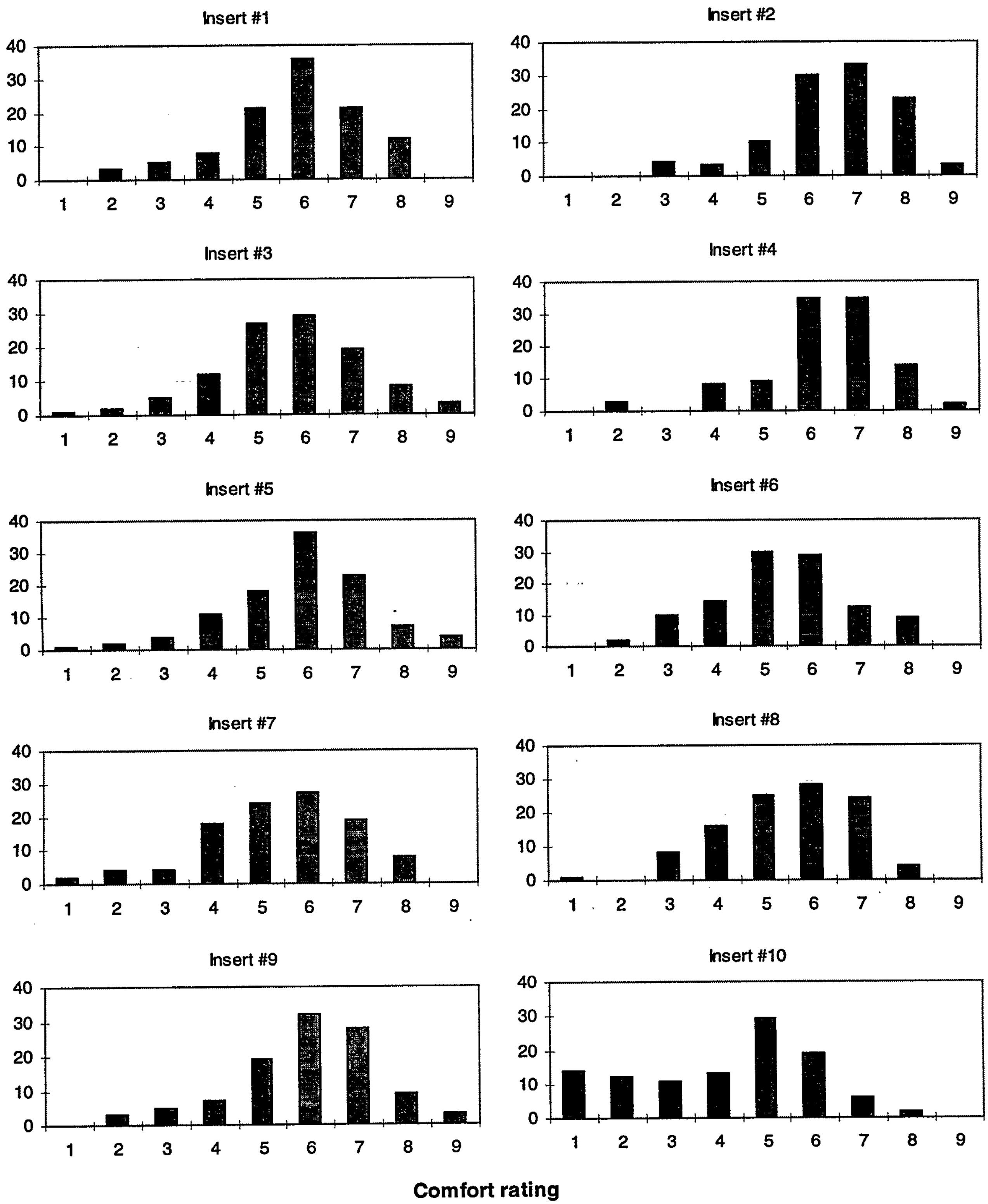


Figure 20. Distribution of comfort ratings for the ten inserts in the walking condition

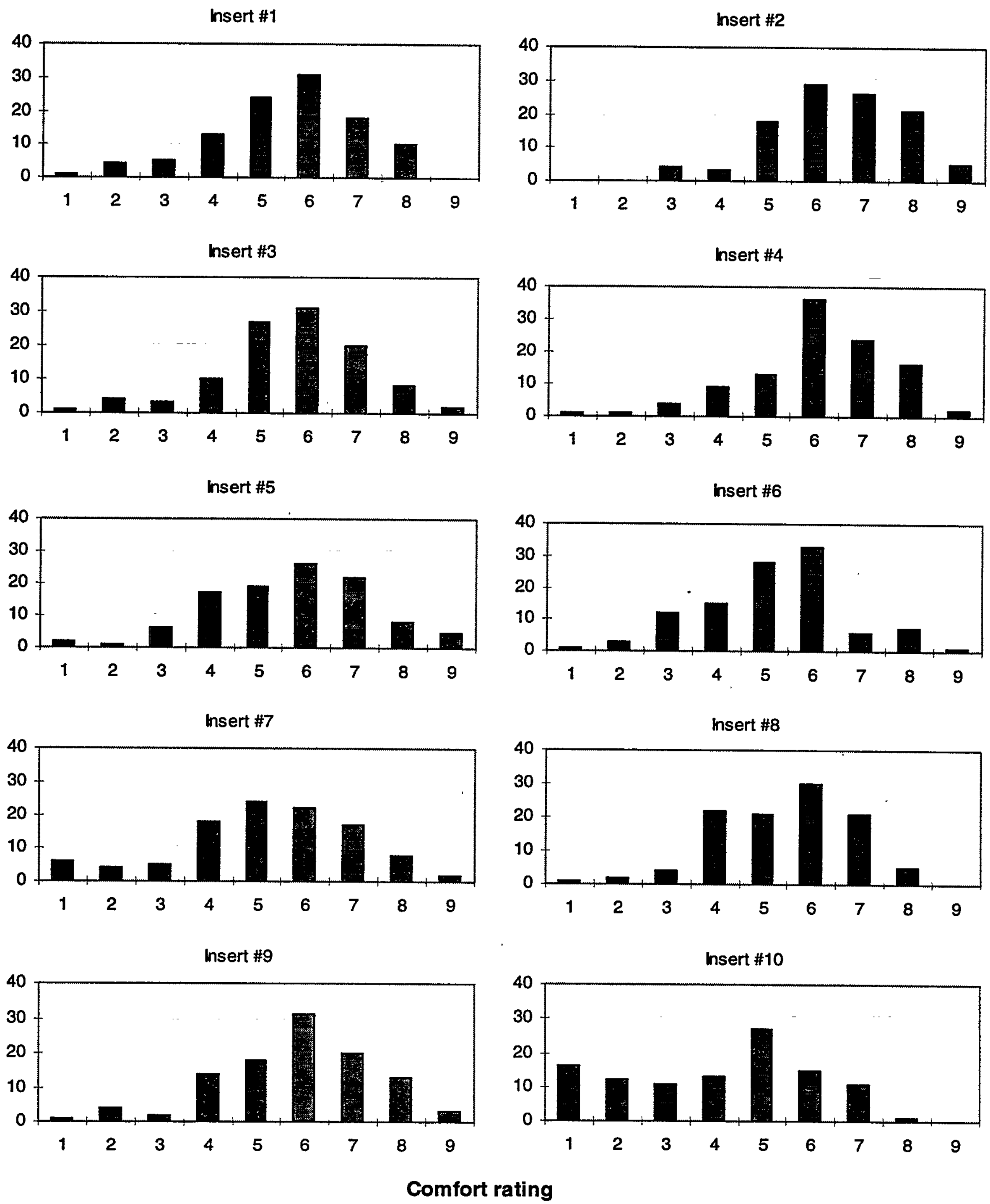


Figure 21. Distribution of comfort ratings for the ten inserts in the running condition.

Differences in comfort ratings

The specifications of the ten different inserts tested in this study along with mean values of their comfort ratings are provided in Table 14 and illustrated in Figure 22. Inserts #2 and #4 had the highest comfort ratings among all tested inserts. The lowest comfort rating on average was given to insert #10.

Table 14. Specifications and mean values of comfort ratings for the ten different inserts.

No.	Arch	Shape	Shape	Material	Material	Material	Elasticity	Elasticity	Comfort rating	
		general	Heel	Heel	Medial Forefoot	Lateral Forefoot	Heel	Forefoot	Walking	running
1	High	Full	Spherical	Hard	Hard	Hard	Elastic	Elastic	6.77	6.49
2	High	Full	Spherical	Soft	Soft	Soft	Elastic	Elastic	7.50	7.32
3	High	Full	Spherical	Soft	Soft	Soft	Viscous	Viscous	6.61	6.61
4	High	Full	Spherical	Soft	Soft	Soft	Viscous	Elastic	7.25	7.03
5	Low	Full	Spherical	Soft	Soft	Soft	Viscous	Elastic	6.82	6.62
6	Low	Full	Flat	Hard	Soft	Hard	Elastic	Elastic	6.31	6.10
7	Low	Full	Flat	Hard	Hard	Soft	Elastic	Elastic	6.38	6.12
8	High	Full	Flat	Soft	Soft	Soft	Viscous	Elastic	6.44	6.40
9	High	Full	Flat	Soft	Soft	Soft	Elastic	Elastic	6.88	6.75
10	High	U-Shaped							5.04	4.93

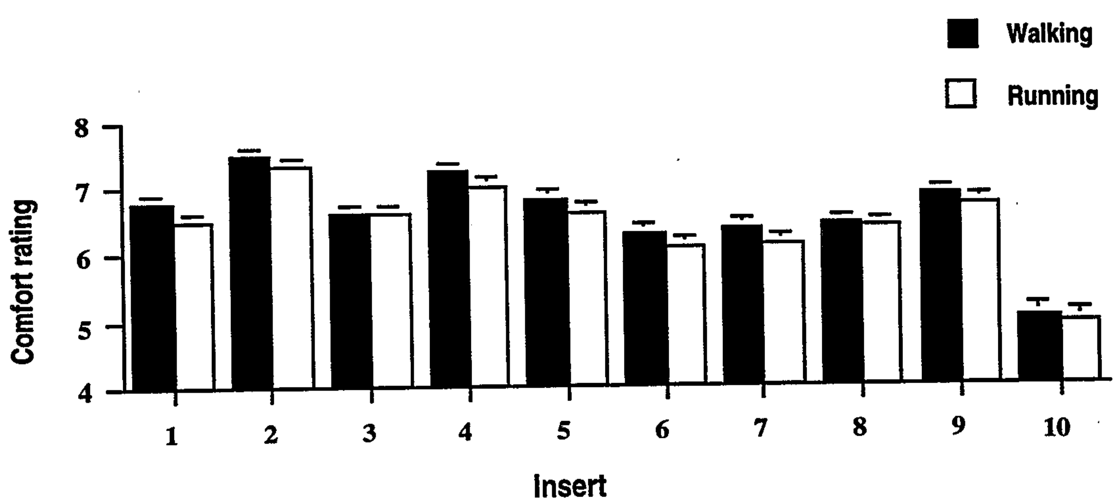


Figure 22. The average comfort ratings with standard error bars for the ten different inserts during walking and running conditions.

The two inserts (#2 and #4) that received the highest comfort rating in this study had similar materials and structure. Both had a high arch support, a spherical heel shape (heel cup), soft and elastic material in the forefoot region, and soft material in the heel region. The only difference between these two inserts was elasticity of the material used in the heel region, i.e. elastic material for #2 and viscous material for #4.

The insert with the lowest comfort rating (#10) does not have any cushioning in the forefoot region. This unique feature was obviously disliked by the majority of the subjects tested. It indicated an important role of forefoot cushioning in the comfort of the shoe. Therefore, an insert without forefoot cushioning is not recommended in terms of comfort.

As shown in Figure 22, the mean value of comfort rating was higher during walking than in running for all ten inserts. Similarly, conditions generally did not change the differences in mean value of comfort ratings between different inserts, for instance, the highest comfort rating was given to insert #2, and the lowest comfort rating was given to insert #10 in both walking and running conditions. A statistical analysis using a multivariate analysis of variance (MANOVA) showed that there was no interaction effect on the mean value of comfort rating between the two conditions (walking and running) and ten different inserts.

A significant difference in comfort rating between walking and running conditions indicated the importance of activity on shoe comfort. Walking and running represented obviously different levels of activity, i.e. running was influenced by the dynamic factors much more than walking. The fact that comfort rating for all tested shoe inserts was systematically higher in walking than in running might be related to several possible factors. One of the possible factors was the design of the inserts. Since all the inserts were made of the same thickness (2-2 ½ mm), they could probably provide enough cushioning for walking, but not for running. Another possible factor was the army boots used for this investigation. The boots were basically hard in the midsole and stiff in the forefoot. The discomfort felt by the subjects due to the hard midsole and stiff forefoot might be increased in running compared to walking. The other possible factor was the change in the level of foot pressure between walking and running conditions. The increased foot pressure during running might exceed the threshold of foot sensitivity that triggered the sensation channel of pain or discomfort.

There was a significant difference between walking and running conditions and a significant difference in comfort ratings among the ten inserts. A post hoc test (Student-Newman-Keuls test) showed significant differences in the mean values of comfort ratings between each of five subsets of the inserts (Table 15). For example, insert #2 was significantly more comfortable than any other insert tested, and insert #10 was significantly less comfortable than any other inserts tested. There was no significant difference in comfort rating within each subset.

The five subsets of inserts divided by post hoc test represented different levels of insert comfort. The features related to the two most comfortable inserts (#2 and #4) and the least comfortable insert (#10) have been discussed above. It was also noticed that the second least comfortable subset of inserts (#6, #7 and #8) had a common feature, that is flat heel shape. Insert #9, the only insert with a flat heel shape which was not included in this subset, was in the third least comfortable subset. The flat heel shape, therefore, is probably one feature responsible for the lower comfort rating of those inserts compared to the inserts with a spherical heel shape.

Table 15. The mean values of comfort rating of ten inserts classified into five subsets based on the results of Student-Newman-Keules test. There is a significant difference in the mean comfort rating between each of the five subsets.

	Subset of inserts				
Insole	**1**	**2**	**3**	**4**	**5**
10	5.00				
6		6.20			
7		6.26			
8		6.42			
3			6.62		
1			6.64		
5			6.73		
9			6.82		
4				7.15	
2					7.42

Criteria C2 ***Subjective pain***

From the comments written by the subjects and the conversation between examiners and subjects, it was found that more than half of the subjects complained about the pain and/or discomfort caused by the high pressure in the dorsal region when they wore the army boots provided. For this reason, some subjects chose boots that were slightly bigger than their foot to relieve the pain and discomfort on the dorsal region. Since the purpose of the study was to evaluate the comfort of shoe inserts, not the boots, the subjects were instructed to ignore the pain or discomfort that they might feel in the dorsal region. The rational for this instruction was to eliminate this systematic factor from comfort rating, therefore, to ensure that the comparison of the inserts would be reflected in the comfort rating given by subjects. However, there were still a few subjects who rated comfort very low for all inserts.

It is, therefore, recommended to modify the design of the army boots on the upper dorsal region. A looser fit in that region will obviously be beneficial for comfort.

One other factor, which some subjects complained about during walking, was the high boot stiffness at the forefoot. The forefoot region of the boots was difficult to bend during walking, but not during running.

Criteria C3 *Pressure distribution*

The peak pressures at five locations under the foot during walking are shown in Figure 23. The peak pressure at the midfoot (medial and lateral arch) was much lower than the other locations with the medial arch being the lowest. The peak pressure at the heel was consistently lower for all ten inserts than at the metatarsal heads and the hallux. The peak pressure at the hallux was higher for inserts (#1, #7, #9 and #10) than the other inserts. At the metatarsal heads, the peak pressure was much higher for insert #10 than any other inserts.

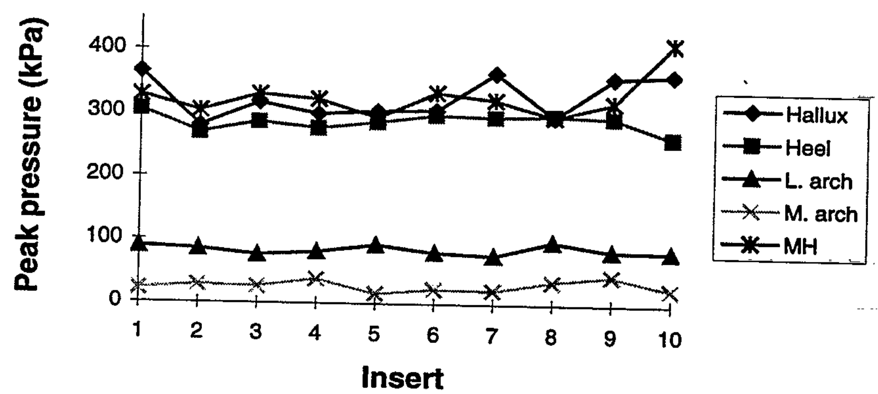


Figure 23. Average values of peak pressures of ten subjects at five different locations of the foot with respect to the ten different inserts.

The average comfort rating of the ten subjects tested for in-shoe pressure is shown in Figure 24 for the different inserts during walking and running. The difference between different inserts was similar to that of the averaged rating from all 106 subjects. Inserts #2 and #4 were the most comfortable inserts while #10 was the least comfort insert. The comfort rating was consistently higher during walking than during running.

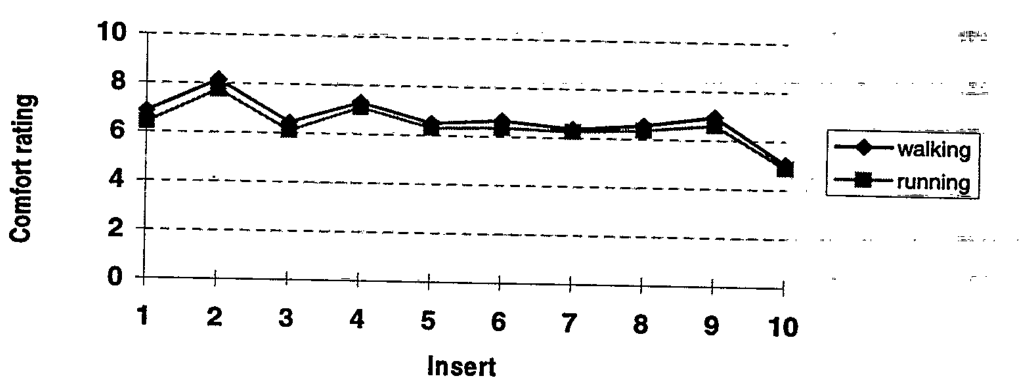


Figure 24. Mean comfort ratings of ten subjects tested with pressure distribution for ten different inserts in walking and running conditions.

When comparing peak pressure values between the most comfortable insert (#2) to the second least comfortable insert (#7) in walking (Figure 25), the lower value of peak pressure was observed at the hallux, the heel and the metatarsal heads for the most comfortable insert. Reduced peak pressure may indicate relief of local irritation from pressure, therefore, more comfort. When comparing the second least comfortable insert (#7) in walking to the least comfortable insert (#10), a significant difference in peak pressure was found at the metatarsal heads (Figure 26). The #10 insert was unique in its shape. Without forefoot cushioning, the peak pressure was mainly increased in the metatarsal head region. This increased pressure led to the increased discomfort felt by the subjects.

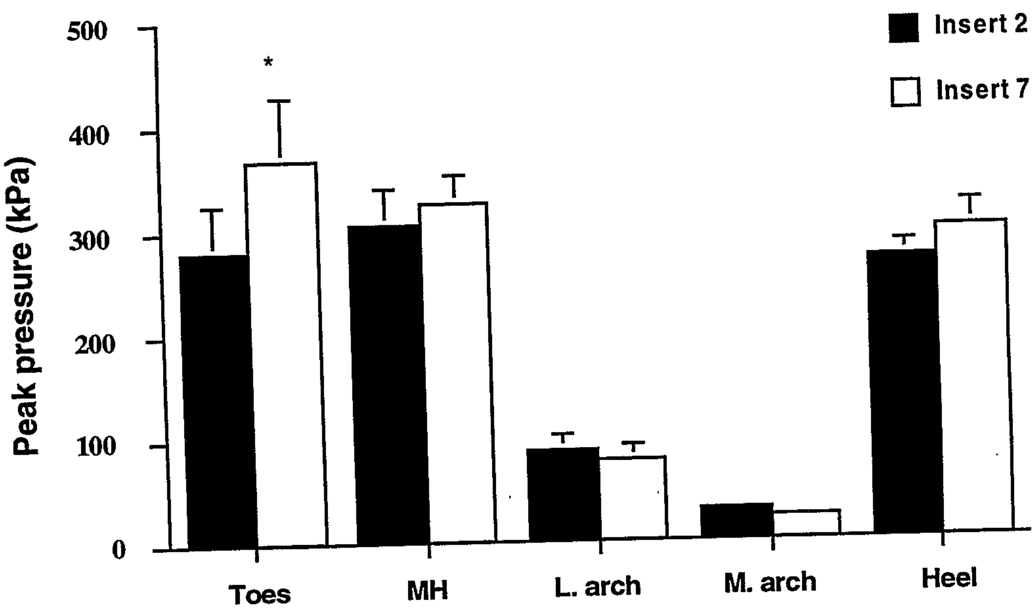


Figure 25. The comparison of peak pressure (mean and standard error) at five different locations of the foot between the most comfortable insert (#2) and the second least comfortable insert (#7) during walking. The symbol (*) indicates the significant difference.

Three pairs of inserts were compared for peak pressure values to examine the influence of single variable difference of the insert on the peak pressure. Each pair of inserts only differed in one aspect. Different materials between inserts #1 and #2 (Figure 27), different arch support between insert #4 and #5 (Figure 28), and different heel shape between inserts #4 and #8 (Figure 29). The comparison showed that the insert made of soft material had significantly lower peak pressure at the hallux, and a trend toward lower peak pressure at the heel and metatarsal head. The insert with a high arch had higher peak pressure at the medial arch area and lower peak pressure at the lateral arch area. The insert with the flat heel shape had slightly higher peak pressure at the heel region. When relating peak pressure to comfort, it was found that the comfort rating decreased when there was an increase in the peak pressure at the hallux, heel, or metatarsal head, but not at the medial arch.

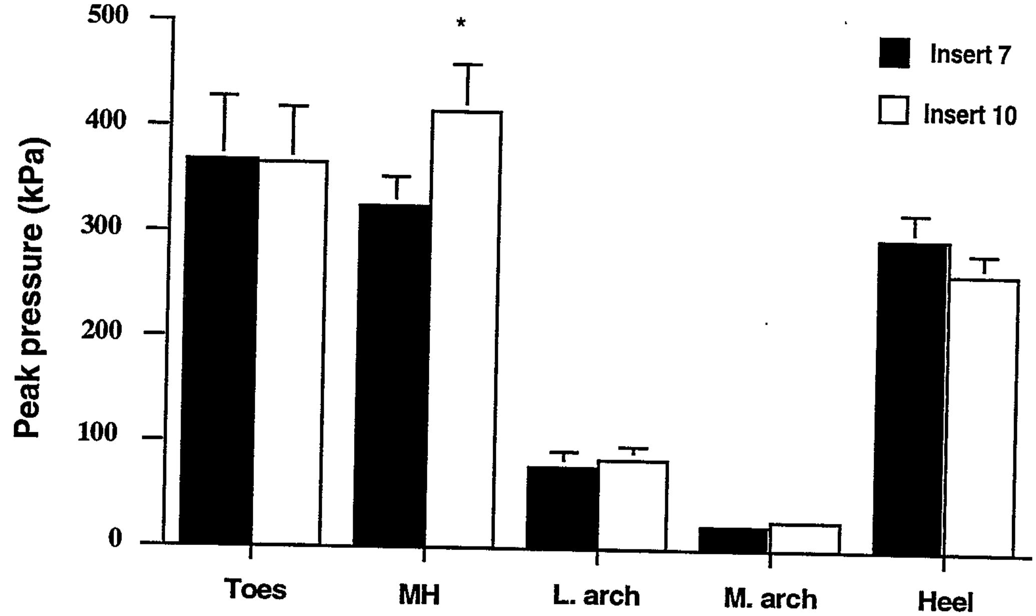


Figure 26. Comparison of peak pressure (mean and standard error) at five different locations of the foot between the second least comfortable insert (#7) and the least comfortable insert (#10) in walking.

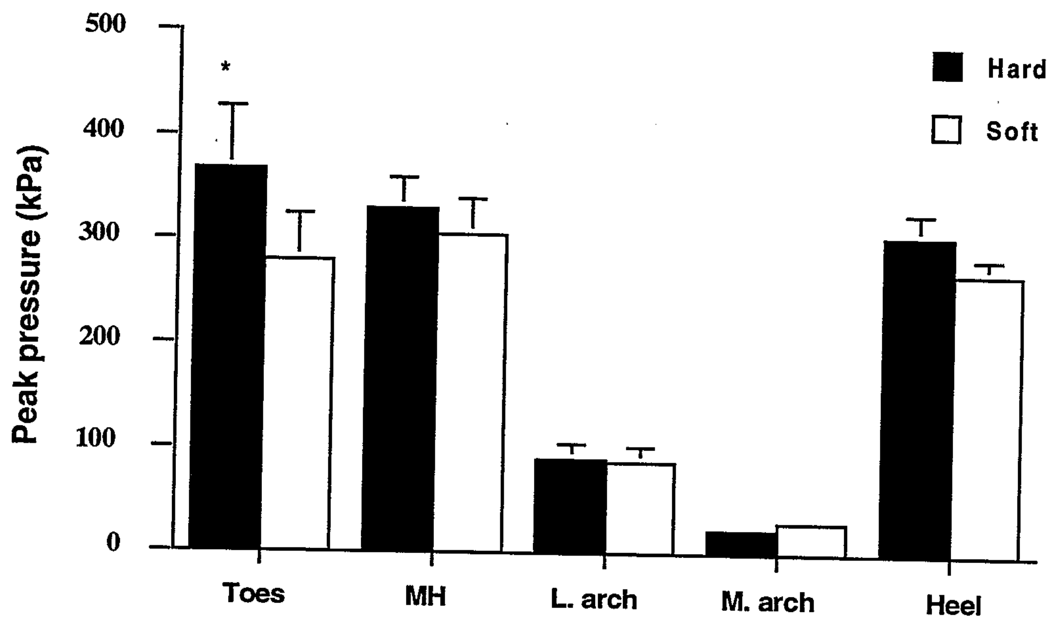


Figure 27. Comparison of peak pressure (mean and standard error) at five different locations of the foot between two inserts with only difference in the material hardness (hard material (#1) versus soft material (#2)). The symbol (*) indicates the significant difference.

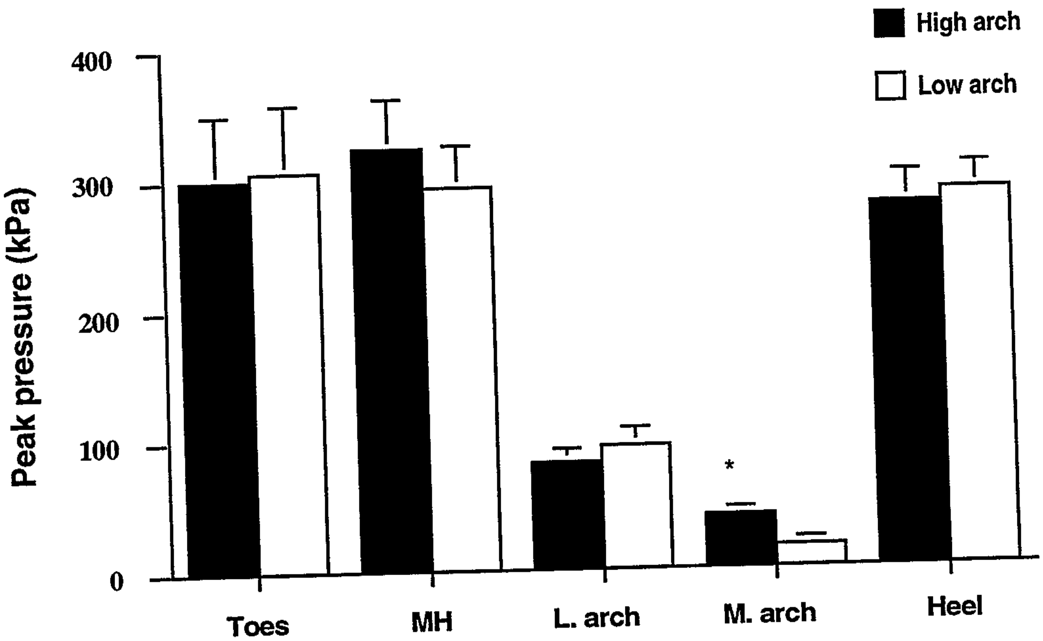


Figure 28. Comparison of peak pressure (mean and standard error) at five different locations of the foot between two inserts with only difference in arch support (high arch (#4) versus low arch (#5)). The symbol (*) indicates the significant difference.

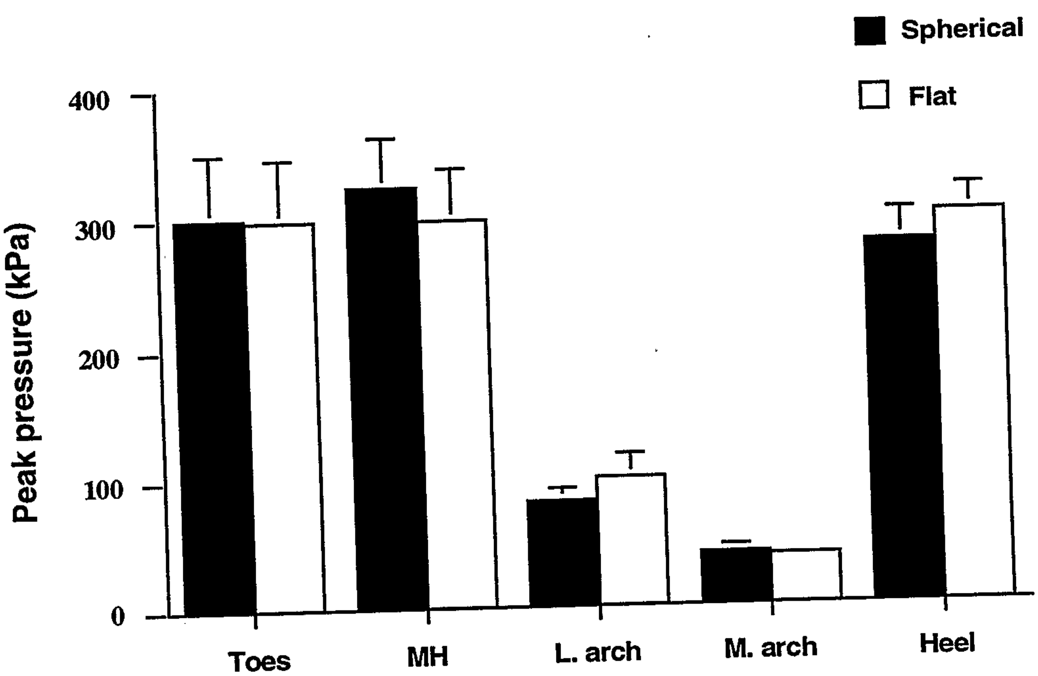


Figure 29. Comparison of peak pressure (mean and standard error) at five different locations of the foot between two inserts with only difference in heel shape (spherical (#4) versus flat (#8)).

There were only minimal and not statistically significant differences in the mean values of d_{COP} between the inserts tested. The largest range was found with insert #3, and the smallest range of d_{COP} with insert #4 (Figure 30). For the ten subjects on whom pressure data was collected, insert #3 was the third least comfortable insert in walking and the second least comfortable insert in running among the ten inserts tested. Additionally, three inserts with higher ranges of d_{COP} (#5, #6 and #10) had low comfort ratings. On the other hand, the two most comfortable inserts (#2 and #4) had low ranges of d_{COP}. Thus, there was a small trend toward lower ranges of d_{COP} being associated with higher comfort ratings. One exception was insert #7 which had the second smallest range of d_{COP} and the second lowest comfort rating in walking.

It is speculated that the range of d_{COP} is a measure of stability. The lower the range, the more stable the insert. It appears that the differences in insert construction used in this study have a minimal influence on stability. Although there is a slight trend toward increased stability being more comfortable, the differences in stability between the inserts are too small to result in any conclusions regarding which insert characteristics influence stability.

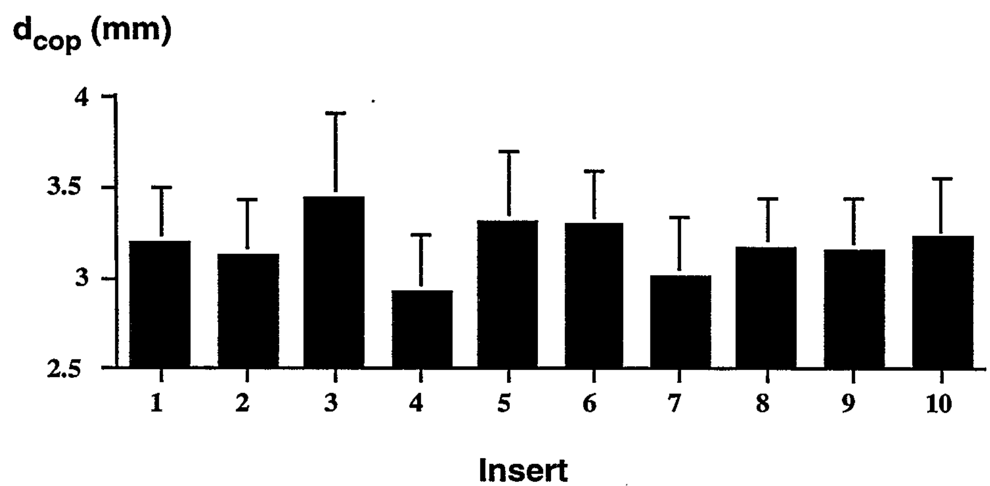
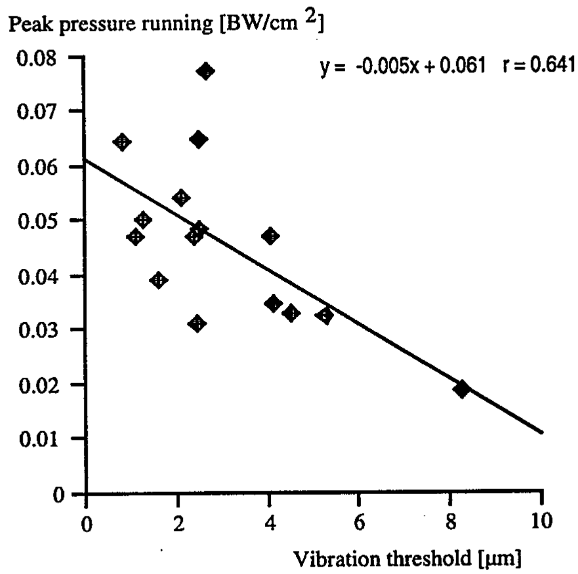


Figure 30. The mean and standard error of range of d_{COP} during walking with respect to each insert.

Relationship between foot sensitivity and in shoe pressure

The sensitivity of the hallux showed a significant correlation with the pressures measured under the hallux (Figure 31). Specifically, a correlation existed between the sensitivity of the hallux to vibrations at 125 Hz with the peak pressures under the hallux while walking ($p=0.02$) and running ($p=0.01$). The higher the sensitivity, the higher the peak pressure. Although not statistically significant, a similar trend existed between the sensitivity of the hallux to vibrations at 30 Hz with peak hallux pressures during running.



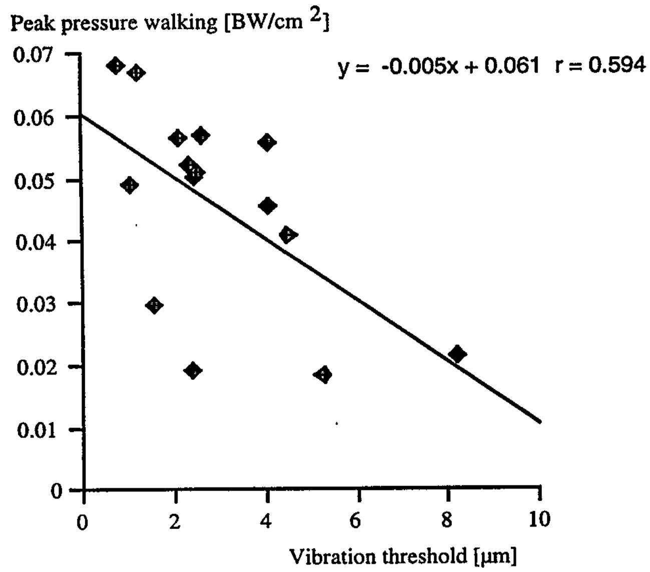


Figure 31. Relationship between the sensitivity of the hallux to vibrations at 125 Hz and the peak pressures under the hallux while running (top) and walking (bottom).

Peak forces during running were significantly correlated with overall mean vibration thresholds at 125 Hz (p=0.038, Figure 32). Once again, a trend, albeit not significant, existed between the peak forces during running and the sensitivity to 125 Hz vibrations at the first metatarsal head (p=0.055), the lateral arch (p=0.095), and the heel (p=0.063). Finally peak forces during running had a significant correlation with the vibration threshold of the lateral arch at 30 Hz (p=0.028). Thus, the higher the sensitivity of the feet to vibration, the higher the peak forces experienced during running.

Peak pressure under the hallux occurs towards the push-off phase of the gait cycle. The negative relationship shows that individuals who are more sensitive to higher frequency vibrations push-off more with their hallux, and hence increase the peak pressure. This may indicate that for individuals with greater sensitivity, the hallux has more of a functional role in stabilizing the foot as the center of pressure moves forward. Another possibility is that the body moves the center of pressure to a point on the foot that is more sensitive to mechanical stimuli. Hamalainen et al. (1992) showed that the body will move the center of pressure to areas of greater sensitivity while standing on a force plate. The results of this study indicate that the same may be true during locomotion. However, it may also be that those subjects who had higher hallux pressures were more pronated towards the end of the gait cycle.

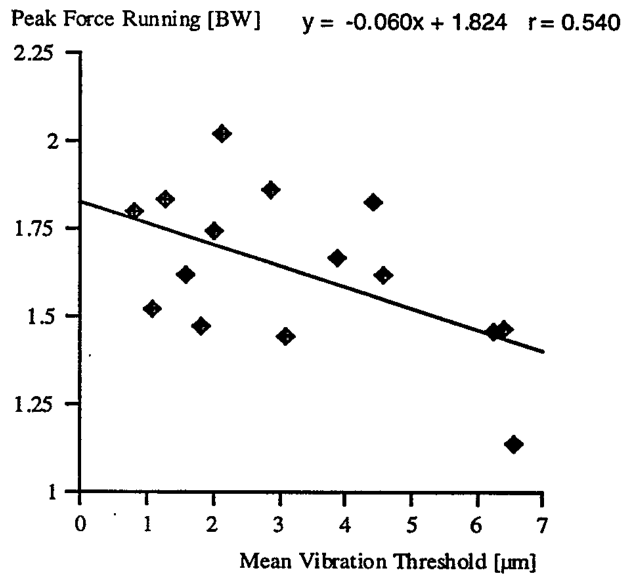


Figure 32. Relationship between individual mean vibration thresholds of all locations at 125 Hz and peak force during running.

The relationship between insert comfort and foot characteristics

Considering the multi-factorial nature of the problem, trends that indicate the correlation between insert comfort rating and foot characteristics (shape, structure, and sensitivity) were analyzed. Two different forms of comparisons were used in this investigation to assess the trends behind the data. The comparisons were made on the comfort rating of nine paired inserts with only a single difference within a pair of the inserts, within seven categories listed below:

1) Soft versus hard elastic material for whole insert:
   #2 and #1
2) Viscous heel versus elastic heel:
   #8 and #9 (both with flat heel shape and soft material)
   #4 and #2 (both with spherical heel shape and soft material)
3) Spherical versus flat heel shape:
   #2 and #9 (both with elastic heel material)
   #4 and #8 (both with viscous heel material)
4) High versus low arch support:
   #4 and #5

5) Viscous and elastic soft material for forefoot:
   #3 and #4
6) Hard elastic versus soft viscous material for whole insert:
   #1 and #3
7) Soft medial, hard lateral forefoot versus hard medial, soft lateral forefoot:
   #6 and #7

The first comparison used ***foot characteristics*** (shape, structure, and sensitivity) as the criterion. For each measured foot characteristic, the insert rating were determined for the subjects (≈10) with the highest and the subjects (≈10) with the lowest foot characteristic values. A large difference in insert comfort rating between the two groups for a specific foot characteristic was used as an indicator that this specific foot characteristic was an important factor.

The second comparison used ***comfort rating*** between two insert conditions as the criterion. Those subjects (≈10) that most preferred the first insert over the second one (group A) were compared with those subjects (≈10) that most preferred the second insert over the first one (group B). Specific foot characteristics were compared for both groups. A large difference in foot characteristics between two groups was used as an secondary indicator that this specific foot characteristic was an important factor.

It was concluded that an agreement in the results of both comparisons indicated strong support for the importance of the specific foot characteristic.

The following sections are results of the two comparisons made on the nine pairs of the inserts. As an example, the analysis procedure for the comparison of insert #2 and insert #1 is described in detail below. The same procedure was used in the comparisons of the other pairs of the inserts.

"General results" of the comparison were obtained from average comfort rating of the two inserts. This rating was higher for insert #2 than insert #1 in both walking (with difference of 0.72 points) and running (with difference of 0.83 points) trials.

"Specific results" of the comparison were based on the two different forms of comparisons, as shown in Figure 33 and Figure 34. For example, the difference between the width of the shoe heel and the width of the heel of the foot, ΔW_{heel}, was found to be an important factor for the comfort rating (Figure 33). The comfort rating from the subjects (≈10) with the highest value of the ΔW_{heel} (high ΔW_{heel}) was higher for the insert #2 (soft) than the insert #1 (hard) by 1.06 points in walking and 0.89 points in running (prefers soft). In contrast, the comfort rating from the subjects (≈10) with the lowest value of the ΔW_{heel} (low ΔW_{heel}) was lower for the insert #2 than the insert #1 by 2.55 points in walking and 1.75 points in running (prefers hard). A small value of the ΔW_{heel} corresponds to a snug fit in the heel of the shoe. Therefore, the subjects with a snug fit preferred hard over soft inserts. This finding was not confirmed in the second comparison. The variable of the ΔW_{heel}, therefore, was not included in Figure 34.

Let's take another example. The vibration sensitivity at the hallux (Vhallux) was found to be an important factor as well (Figure 33). The comfort rating from the subjects (≈10) with the highest value of the Vhallux (high Vhallux) was higher for the insert #2 (soft) than for the insert #1 (hard) by 2.5 points in walking and 2.5 points in running (prefers soft). In contrast, the comfort rating from the subjects (≈10) with the lowest value of the Vhallux (low Vhallux) was higher for the insert #2 than the insert #1 by only 0.39 points in walking and 0.83 points in running (prefers soft). Therefore, the subjects with high vibration sensitivity at the hallux made a strong statement for the soft insert. This finding was confirmed in the second comparison (Figure 34). The vibration sensitivity threshold was 1.6 for the subjects (≈10) with highest comfort rating for the insert #2 (soft) over insert #1 (hard). In contrast, the vibration sensitivity threshold was 2.92 for the subjects (≈10) with highest comfort rating for the insert #1 (soft) over insert #2. Therefore, subjects who preferred the soft insert over the hard one had high vibration sensitivity (low sensitivity threshold). In this case, the importance of the vibration sensitivity at the hallux was strongly supported.

1) Soft – hard elastic material (whole insert): #2 – #1

General results:
In general, the test subjects preferred the soft over the hard insert. On average the soft insert was rated 0.72 comfort points higher for walking and 0.83 comfort points higher for running.

Specific results:

- ***Heel width:*** Subjects with a small difference between the width of the shoe heel and the width of the heel of the foot, ΔW_{heel}, which corresponds to a snug fit in the heel of the shoe, preferred hard over soft inserts (difference 3.61 to 2.64 comfort points difference). This was the only subgroup that preferred the hard insert (Figure 33). This result was not confirmed in the group comparison of the comfort rating between soft and hard.
- ***Hallux height:*** Subjects with a high difference between the hallux heights of shoe and foot (a loose fit of the shoe around the hallux) did not distinguish between soft and hard. However, subjects with a tight fit at the hallux preferred a soft insert (Figure 33). The pressure at the hallux may have overridden everything else. This result was not confirmed in the group comparison of the comfort rating between soft and hard.
- ***Heel alignment:*** Subjects with a well-aligned foot (rearfoot angle) did not favor soft or hard insert materials. However, subjects with a poorly aligned rearfoot (larger foot eversion) preferred soft inserts (Figure 33). This result was not confirmed in the group comparison of the comfort rating between soft and hard.
- ***Foot sensitivity:*** Subjects with a high tactile and vibration sensitivity at the heel showed a strong preference for soft inserts. However, subjects with a low tactile and vibration sensitivity at the heel did not distinguish between soft and hard inserts (Figure 33). Similarly, subjects with high vibration sensitivity at the hallux made a strong statement for the soft insert (2.5 comfort points difference for walking and running). Both results were confirmed in the group comparison of the comfort rating between soft and hard (Figure 34).

Synthesis:
Most subjects preferred the soft inserts over the hard ones. A combination of several factors may have been the reason for this choice.
First, the available space between foot and shoe may have played a role. A soft insert may have allowed more abrasive micro-movement, increasing the shear stresses, which could have been uncomfortable for those subjects with a tight fit. For the hallux, tightness has produced increased pressure (Figure 31). Thus, if there is not enough space (tight fit), a soft insert may have allowed an easier adjustment.
Second, the alignment of the foot and leg may have played a role. Subjects with a poorly aligned foot may have preferred the soft insoles because they allowed for an easier adjustment and possible correction for the malalignment.
The strongest factor in the selection of soft over hard was the foot sensitivity. For those subjects that had highly sensitive heels, soft inserts were very important. This may have been related to

impact loading. Soft inserts are assumed to reduce amplitude and frequency of the input signals. Subjects that are highly sensitive would, therefore, consider such soft inserts as more comfortable. Additionally, soft inserts were important for subjects with high vibration sensitivity at the hallux. This result may have been associated with the pressure under the hallux. Pressure measurements showed significantly higher peak pressures under the hallux for the hard inserts compared to the soft ones (Figure 31). Thus, the hard inserts would produce a signal with a higher amplitude and mean frequency compared to the soft insert, a result, which is not liked by subjects with high vibration sensitivity.

GENERAL RESULT	Soft preferred over hard	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
HEEL WIDTH	Tight fit preferred hard	
HALLUX HEIGHT	Tight fit preferred soft	
HEEL ALIGNMENT	Not well aligned heel preferred soft	
FOOT SENSITIVITY	Sensitive heel (tactile and vibration) preferred soft Vibration sensitive hallux preferred soft	Subjects who preferred soft had a sensitive heel (tactile and vibration) Subjects who preferred soft had a sensitive hallux (vibration)

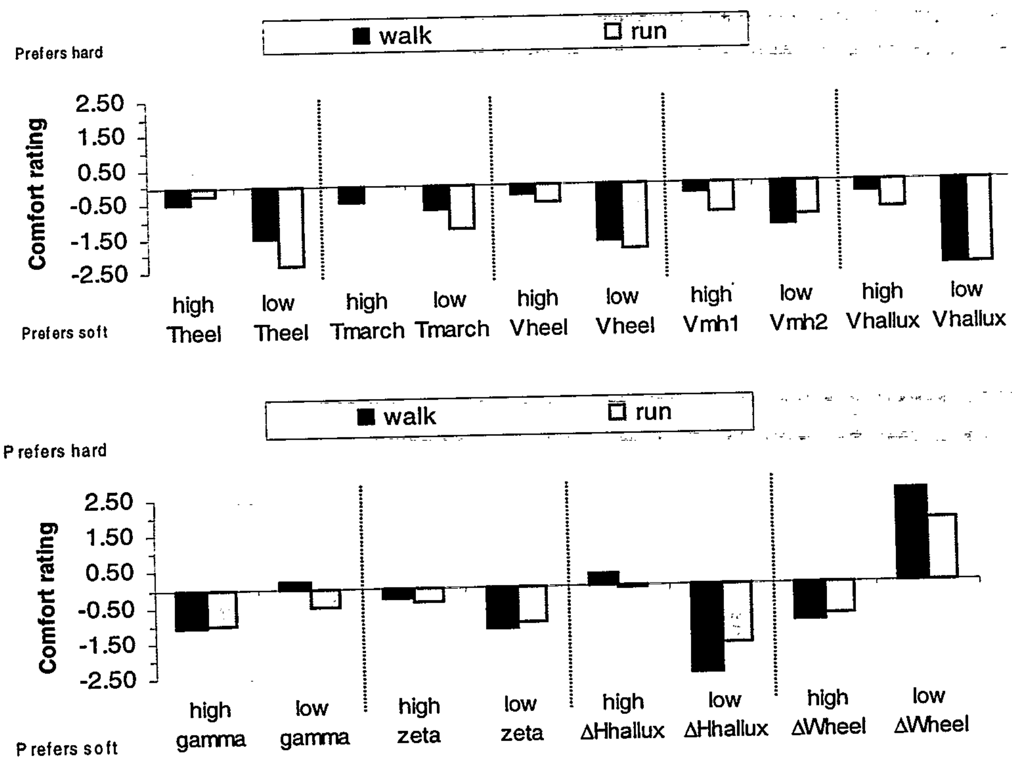


Figure 33. Comparison of differences in comfort ratings between hard (insert #1) and soft (insert #2) inserts for subject groups divided according to foot characteristics.

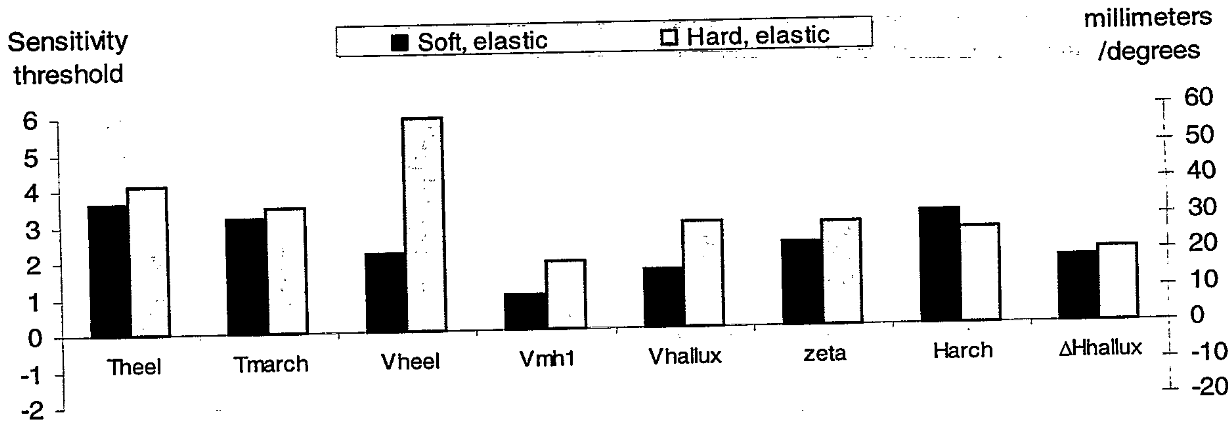


Figure 34. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between the hard (insert #1) and soft (insert #2) inserts.

2) Viscous heel – elastic heel:
#8 - #9 (both with flat heel, soft material)

General results:
In general, the subjects preferred the elastic heel over the viscous heel. The average comfort rating for the elastic heel insert was 0.44 points higher for walking and 0.62 points higher for running.

Specific results:

- ***Heel width:*** Subjects with a low difference between the width of the boot and the width of heel, a tight fit, strongly preferred the viscous heel insert. Conversely, the subjects with the loosest fit preferred the elastic heel, especially while walking (Figure 35). These results were not supported when the groups were compared based on comfort ratings of the two inserts (Figure 36).
- ***Subtalar alignment:*** Subjects with a poorly aligned ankle (high beta) found the elastic heel to be substantially more comfortable while walking and running. The subjects with a well aligned ankle did not make a preference for either insert (Figure 35). When analyzing the subjects according to comfort rating, these results are not supported with only a 2.5° difference between the two groups (Figure 36).
- ***Foot sensitivity:*** Subjects who had the lowest tactile sensitivity at the medial arch strongly preferred the elastic heel while running. The subjects with the highest sensitivity at the medial arch did not make a preference for either insert (Figure 35). This result was not supported by group comparisons of insert comfort ratings (Figure 36). Vibration sensitivity at the heel did not influence the choice of inserts. At both the first metatarsal head and hallux, the subjects with low sensitivity preferred the elastic heel, while those who were more sensitive preferred the viscous heel. This result was supported by the group comparison of comfort ratings between viscous and elastic heel inserts (Figure 36).

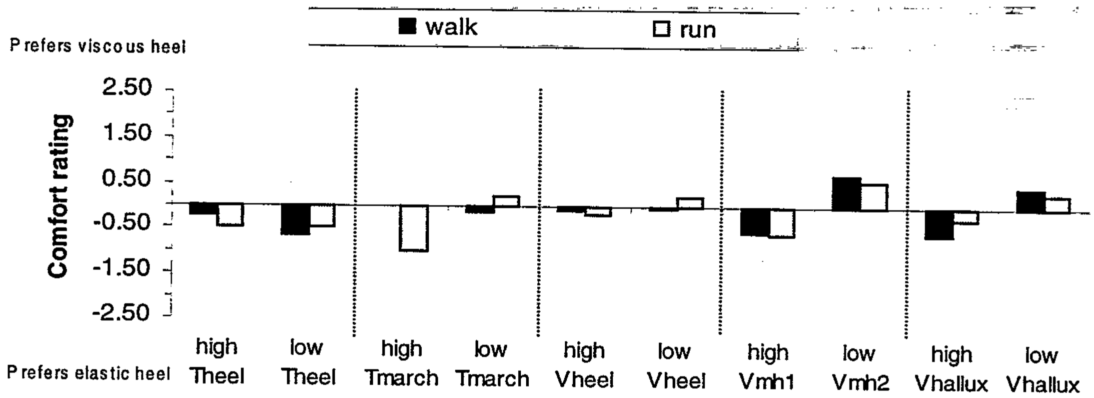
Synthesis:

In general, the subjects preferred the elastic heel over the viscous heel. However, the difference between the two inserts was small. Several factors seemed to influence the comfort rating for specific groups.
First, the fit of the boot may have influenced the comfort ratings. For subjects with a tight fit at the heel, a viscous insert was preferred over the elastic insert. A viscous insert may have reduced the amount of movement and, therefore, have limited abrasive forces around the heel.
Second, skeletal alignment may be an important factor in determining the comfort level of a particular insert. Subjects with a poorly aligned subtalar joint found the elastic insert to be more comfortable. This result is counter intuitive because it was expected that a viscous heel would reduce the amount of movement compared to an elastic heel and, therefore, limit the risk of this malalignment.

Finally, the sensitivity of the foot to tactile and vibration stimuli was a factor in the comfort rating of elastic and viscous heel inserts. Individuals who were highly sensitive at the metatarsal head and hallux preferred viscous heel inserts. While a viscous material would damp input vibrations during impact, it is unknown why a viscous heel was preferred by subjects with a sensitive midfoot and forefoot.

However, these discussed possible effects were minimal. The primary finding of the comparison between the flat elastic and viscous heels was that the two solutions were rated at about the same comfort level. All other results were possible but rather weak trends.

GENERAL RESULT	Elastic preferred slightly over viscous heel. For practical purposes little difference.	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
HEEL WIDTH	Tight fit preferred viscous heel Loose fit preferred elastic heel	
SUBTALAR ALIGNMENT	Not well aligned subtalar joint preferred elastic heel	
FOOT SENSITIVITY	Less sensitive medial arch (tactile) preferred elastic heel while running Sensitive first metatarsal head and hallux (vibration) preferred viscous heel	Subjects who preferred viscous heel were more sensitive at the first metatarsal head and hallux



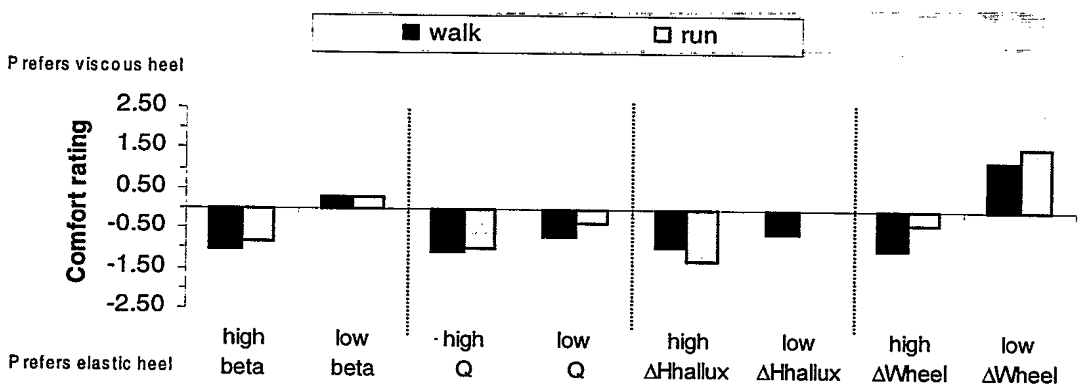


Figure 35. Comparison of differences in comfort ratings between a viscous heel (insert #8) and an elastic heel (insert #9) for subject groups divided according to foot characteristics.

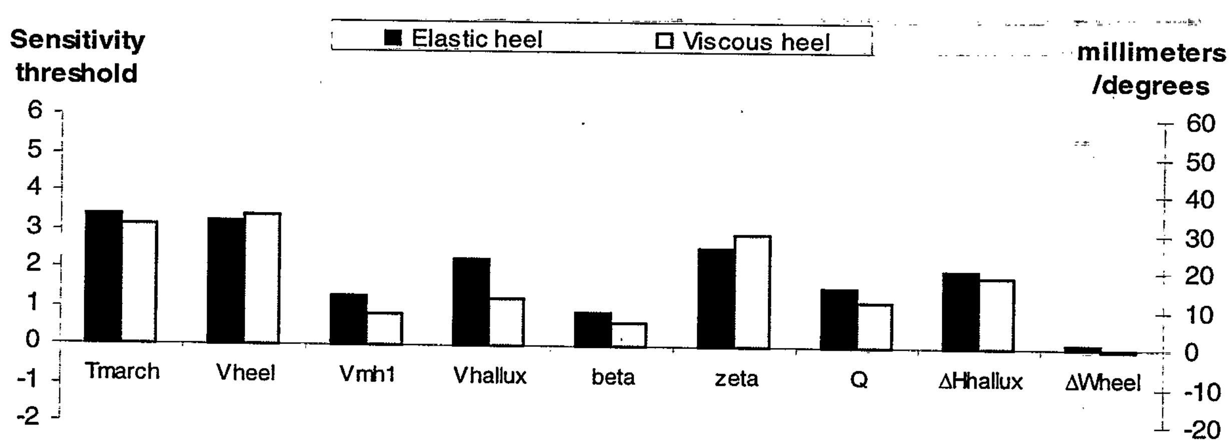


Figure 36. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between a viscous heel (insert #8) and an elastic heel (insert #9).

2) Viscous heel – elastic heel:
#4 – #2 (both with spherical heel, soft material)

General results:
For the most part, there was little overall difference between the comfort rating of the two inserts. The elastic, spherical heel insert (2) was rated as the most comfortable insert. The viscous, spherical insert (4) had an overall rating as the second most comfortable insert. The difference in comfort ratings was only 0.25 points for walking and 0.29 for running.

Specific results:

- ***Heel width:*** Subjects with a tight fit at the heel (low ΔWheel) rated the viscous heel more as more comfortable during walking. The subjects with a loose fit tended to prefer the elastic heel (Figure 37). These results were not supported by the group comparisons of insert comfort rating.
- ***Arch height:*** Subjects with a high arch strongly preferred the elastic heel insert. The difference in comfort rating was more than 1.2 points compared to the subjects with the lowest arches (Figure 37). These results were not supported by the group comparisons of comfort rating. The difference in arch height between the subjects who most preferred the viscous and those who most preferred the elastic heel was only 2.5 mm (Figure 38).
- ***Subtalar alignment:*** Subjects with poorly aligned subtalar joints (high beta) preferred the elastic heel insert. Those will well aligned subtalar joints made no preference for inserts. These results were not confirmed by the group comparisons of comfort rating.
- ***Leg torsion:*** Subjects with high torsion (high zeta) preferred the viscous heel. The subjects with low leg torsion rated the elastic heel as more comfortable (difference in comfort 1.5 points, Figure 37). These results were supported when the subjects were grouped according to comfort rating (Figure 38).
- ***Q angle:*** Subjects with the largest Q-angle made a strong preference towards the elastic heel. The subjects with the smallest Q-angles did not make a preference for either the elastic or viscous heel inserts. These results were in accordance with the group comparisons of comfort rating. The subjects who most preferred the elastic inserts had a Q-angle 8.3° higher than the subjects who preferred the viscous heel (Figure 38).
- ***Foot sensitivity:*** Subjects who were highly sensitive to tactile and vibration stimuli at the heel made a strong preference for the elastic heel insert (Figure 37). Those who were less sensitive did not rate one insert over another. At the first metatarsal head and hallux, the subjects with high vibration sensitivity preferred the elastic insert, compared to the less sensitive subjects who did not distinguish between the two inserts (Figure 37). All of these results were not supported when grouping by comfort rating (Figure 38).

Synthesis:
Overall, there was little difference in the mean ratings of the two inserts. However, the preference for elastic or viscous heel inserts was different for different subgroups. Several factors were important in their decisions.

The fit of the boot played a role in the subjective comfort rating. Subjects with a tight fit at the heel rated the viscous heel insert as more comfortable than the elastic heel insert. A viscous insert may have reduced the amount of movement in heel and effectively reduce the abrasive forces at the heel.

Skeletal alignment was an important factor in the subjective assessment of comfort. Subjects with a poorly aligned subtalar joint and/or larger Q-angles found the elastic insert to be more comfortable. This is counter intuitive because it would be expected that a viscous insert may reduce the amount of movement, and therefore limit the risk of further malalignment. In contrast subjects with high tibial torsion preferred the viscous insert thereby limiting the risk of further malalignment

Finally, the sensitivity of the foot was of importance in the difference in comfort rating of these two inserts. Subjects who were more sensitive at the heel made preference for the elastic heel. It may be that the soft material was the overriding factor in the inserts overall comfort rating. The viscous heel and elastic heel inserts were composed of a soft material and were ranked as the top two most comfortable inserts. At high loading rates the stiffness of a viscous material increases, and therefore, influenced the perceived comfort of the sensitive subjects.

Poor skeletal alignment, therefore, did not result in the same preferred strategies with respect to elastic or viscous inserts. It was speculated that viscous inserts would be preferred in general when skeletal alignment was poor. However, this speculation could not be confirmed for all variables tested.

GENERAL RESULT	No difference between elastic and viscous heel	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
HEEL WIDTH	Tight fit preferred viscous heel insert	
ARCH HEIGHT	High arch preferred elastic heel insert	
SUBTALAR ALIGNMENT	Poorly aligned subtalar joints prefer elastic heel insert	
TIBIAL TORSION	High tibial torsion preferred viscous heel	Subjects who preferred the viscous heel had higher tibial torsion
Q-ANGLE	Large Q-angle preferred elastic heel insert	Subjects who preferred an elastic heel had a higher Q-angle
FOOT SENSITIVITY	Sensitive at heel (tactile and vibration) prefer elastic insert Sensitive at first metatarsal head and hallux (vibration) prefer elastic heel	

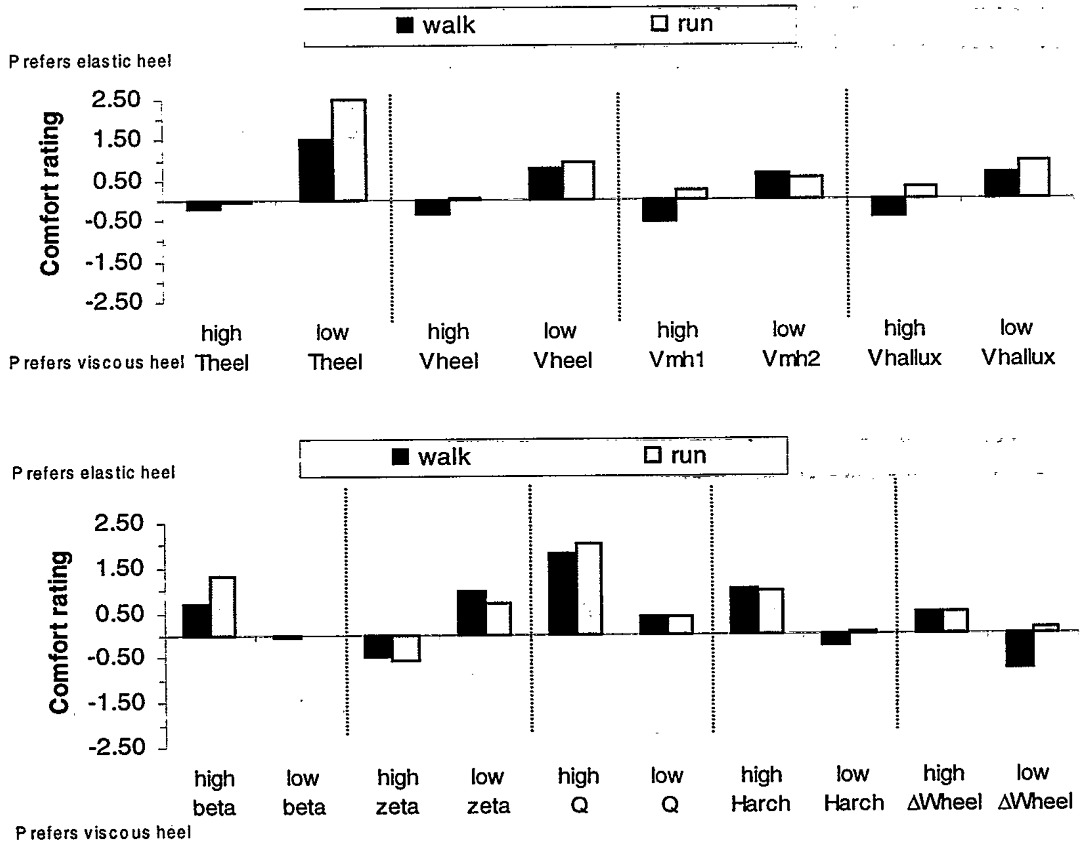


Figure 37. Comparison of differences in comfort ratings between a viscous heel (insert #4) and an elastic heel (insert #2) for subject groups divided according to foot characteristics.

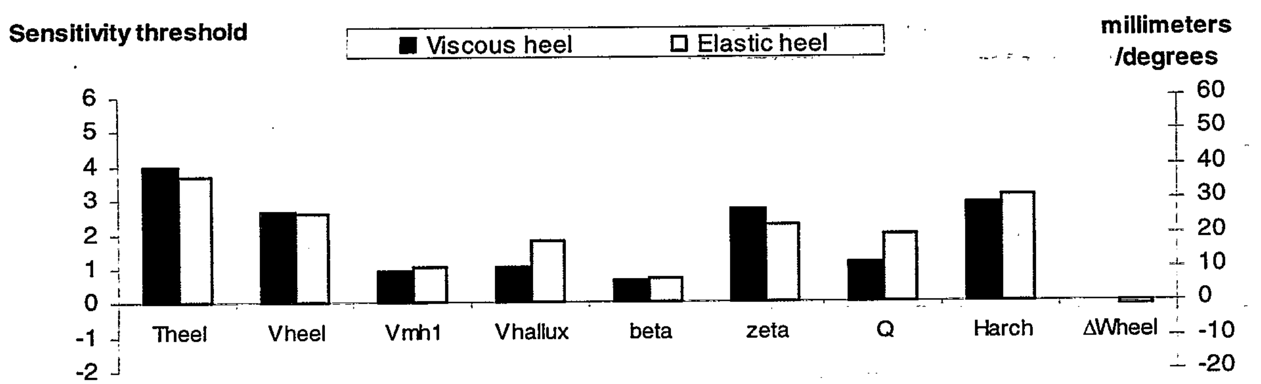


Figure 38. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between a viscous heel (insert #4) and an elastic heel (insert #2).

3) Spherical heel – flat heel:
#2 – #9 (both with elastic heel materials)

General results:

In general, the test subjects preferred the spherical heel over the flat heel. On average the spherical insert was rated 0.62 comfort points higher for walking and 0.57 comfort points higher for running.

Specific results:

- ***Arch height:*** Subjects with a high arch preferred an insert with a spherical heel (Figure 45). This result was not confirmed in the group comparison of the comfort rating between the spherical and flat heel (Figure 46).
- ***Foot sensitivity:*** Subjects with a high tactile and vibration sensitivity at the heel showed a strong preference for the spherical heel. Subjects with a more sensitive (tactile) medial arch preferred a spherical heel while subjects with a less sensitive medial arch preferred a flat heel (Figure 45). These results were not confirmed in the group comparison of the comfort rating between the spherical and flat heel.

Synthesis:

Most subjects preferred the insert with the spherical heel over the insert with the flat heel. Subjects with a high arch preferred a spherical heel. One possible explanation for this result is that subjects with a high arch have a substantial elongation of the foot during dynamic loading. A spherical heel would limit excessive posterior translation of the heel with respect to the boot. For those subjects that had highly sensitive heels, spherical inserts were very important. This may have been related to impact loading. The spherical heel constrains the fat pad under the calcaneus providing increased shock absorption during landing. Subjects that are highly sensitive would, therefore, consider such inserts as more comfortable. Speculations for the reason why a flat heel was preferred by subjects with a less sensitive midfoot are not available.

GENERAL RESULT	Spherical heel preferred over flat heel	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
ARCH HEIGHT	High arch preferred spherical heel	
FOOT SENSITIVITY	High sensitivity (tactile and vibration) at the heel prefer spherical heel High sensitivity (tactile) at the medial arch prefer spherical heel Low sensitivity (tactile) at the medial arch prefer flat heel	

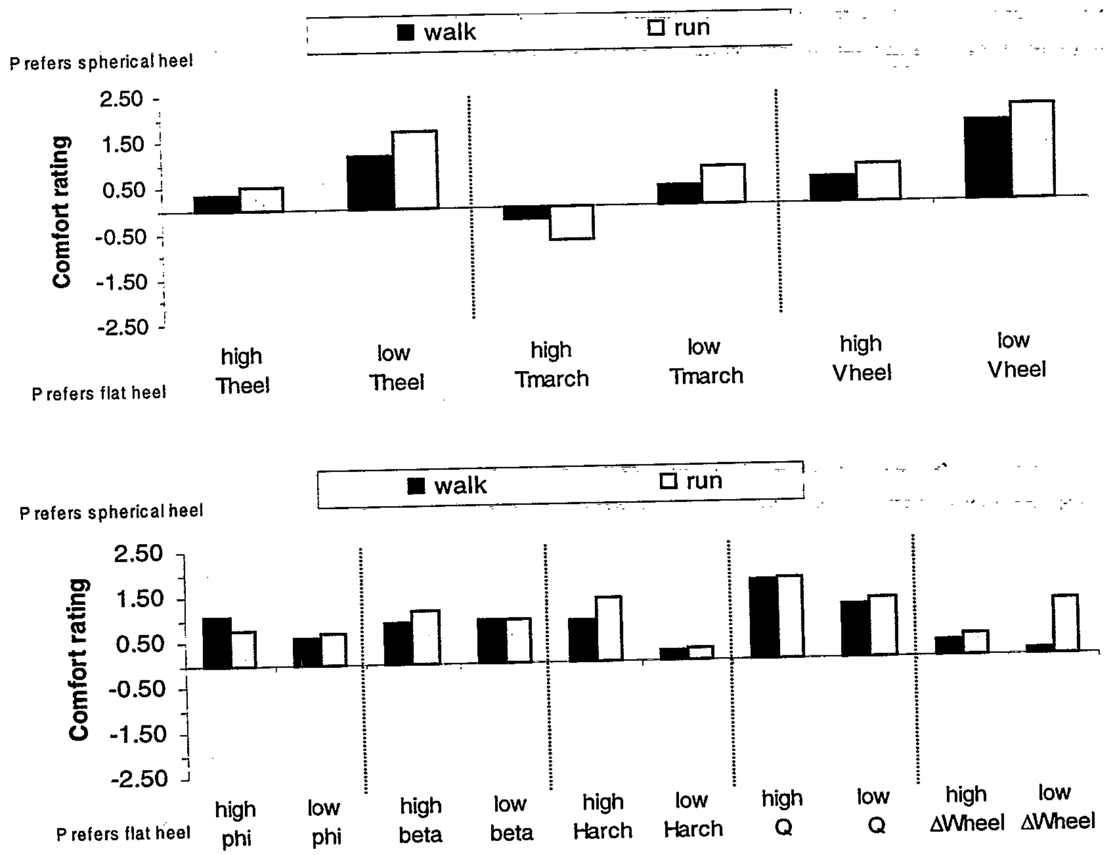


Figure 45. Comparison of differences in comfort ratings between a spherical heel (insert #2) and a flat heel (insert #9) for subject groups divided according to foot characteristics.

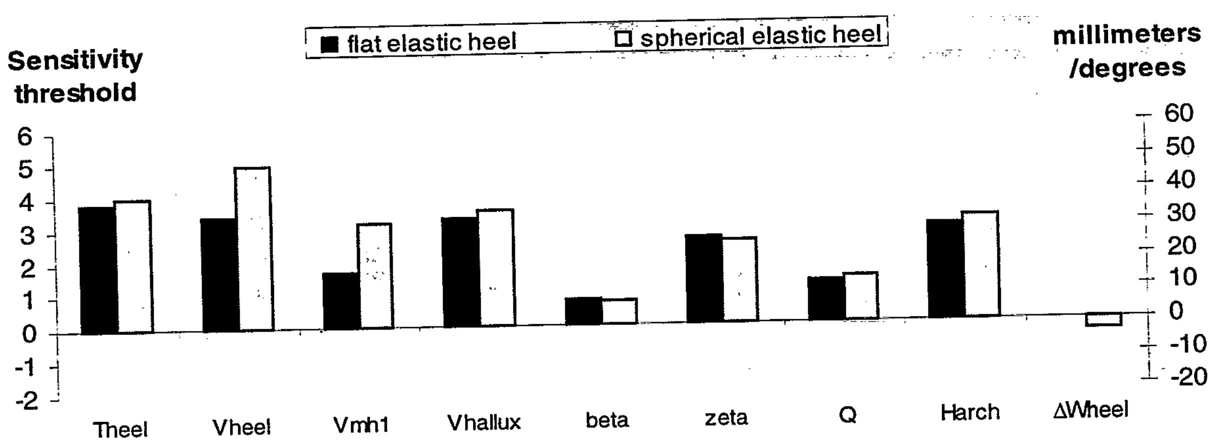


Figure 46. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between a spherical heel (insert #2) and a flat heel (insert #9).

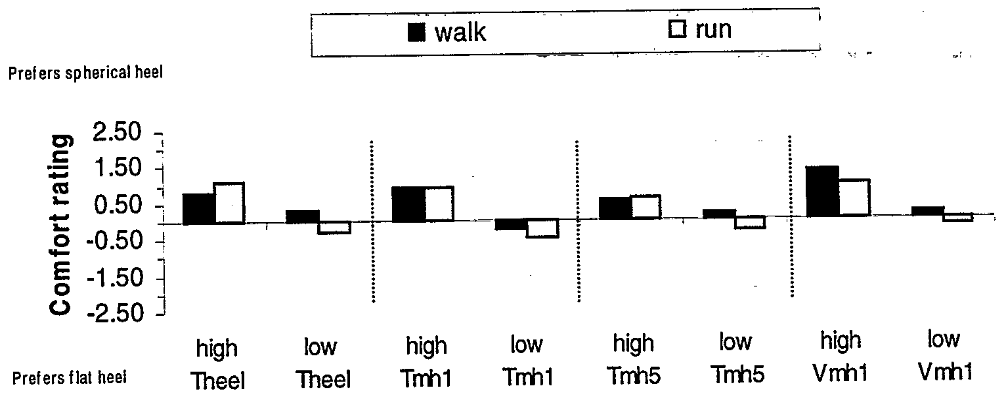
3) Spherical heel – flat heel:
#4 – #8 (both with viscous heel materials)

General results:
In general, the test subjects preferred the spherical heel over the flat heel. On average the spherical insert was rated 0.81 comfort points higher for walking and 0.63 comfort points higher for running.

Specific results:
- ***Heel width:*** Subjects with a small difference between the width of the shoe heel and the width of the heel of the foot, (ΔW_{heel}), which corresponds to a snug fit in the heel of the shoe, preferred flat over spherical inserts (Figure 47). This result was not confirmed in the group comparison of the comfort rating between spherical and flat heels (Figure 48).
- ***Foot sensitivity:*** Less sensitive subjects (tactile and vibration) at the first metatarsal head preferred a spherical heel. Similarly, less sensitive subjects (tactile) at the heel and fifth metatarsal head preferred a spherical heel (Figure 47). These results were not confirmed in the group comparison of the comfort rating between spherical and flat heels.

Synthesis:
Most subjects preferred the inserts with the spherical heel over the inserts with the flat heel. This result is a confirmation of the results of the previous comparison between spherical and flat heels with elastic materials. Thus, spherical heels are the preferred solution independent of the elasticity or viscosity of the heel.
There were no large differences in any of the foot characteristics, which could be used to account for this preference. The only (weak) statement, which could be made is that the subjects with a tight fit at the heel preferred the insert with the flat heel. Thus, although a spherical heel appears to be a comfortable insert characteristic, there must be enough space for the heel to allow movement of the soft tissue of the heel pad.
Although specific tactile sensitivity measurements showed that insensitive subjects strongly preferred a spherical heel, this only reinforced the general trend toward a preference of a spherical heel.

GENERAL RESULT	Spherical heel preferred over flat heel	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
HEEL WIDTH	Tight fit preferred flat heel	
FOOT SENSITIVITY	Less sensitive (tactile and vibration) at first metatarsal head prefer spherical heel Less sensitive (tactile) at heel and fifth metatarsal head prefer spherical heel	



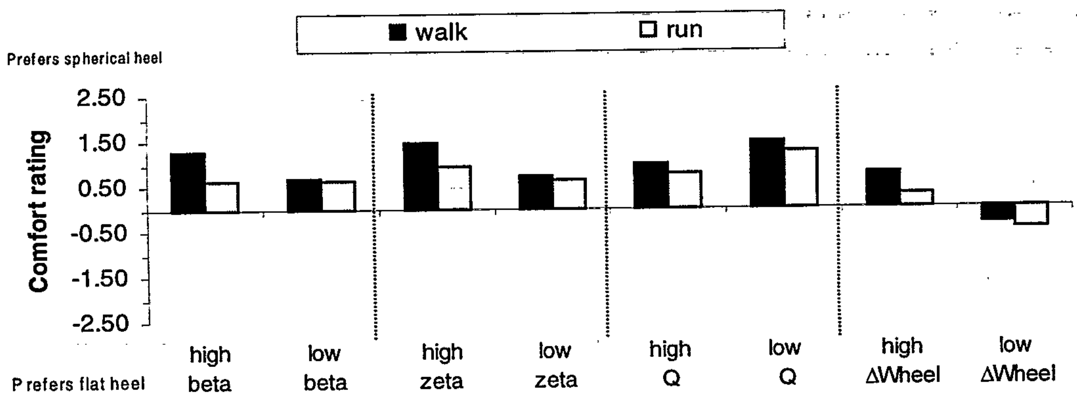


Figure 47. Comparison of differences in comfort ratings between a spherical heel (insert #4) and a flat heel (insert #8) for subject groups divided according to foot characteristics.

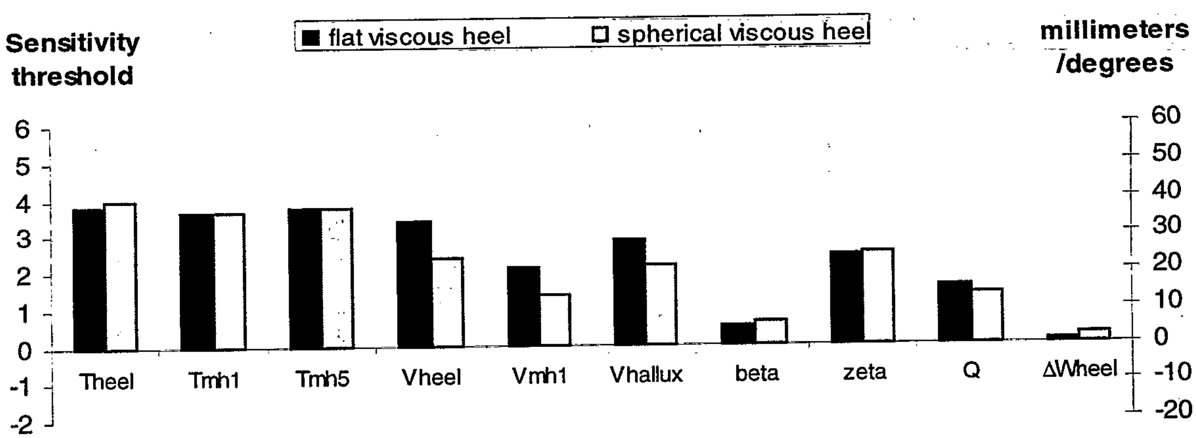


Figure 48. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between a spherical heel (insert #4) and a flat heel (insert #8).

4) High – low arch:
#4 – #5

General results:
In general, the test subjects preferred the high arch over the low arch insert. On average the high arch insert was rated 0.43 comfort points higher for walking and 0.41 comfort points higher for running.

Specific results:

- ***Forefoot width:*** Subjects with a loose fit at the forefoot (high $\Delta W_{forefoot}$) preferred high over low arch inserts (about 1.5 comfort points difference) (Figure 43). This result was confirmed in the group comparison of the comfort rating between high and low arch.
- ***Arch height:*** Subjects with a low arch foot preferred a high arch insert. However, subjects with a high arch foot did not distinguish between high and low arch inserts. (Figure 43). This result was not confirmed in the group comparison of the comfort rating between high and low arch.
- ***Q-angle***: Subjects with a high Q angle preferred low arch inserts. Subjects with a low Q angle preferred high arch inserts (Figure 43). This result was confirmed in the group comparison of the comfort rating between high and low arch (Figure 44).
- ***Subtalar alignment:*** Subjects with a well-aligned subtalar joint (low beta) preferred high arch inserts. Subjects with a poorly aligned subtalar joint (high beta) showed no preference (Figure 43). This result was not confirmed in the group comparison of the comfort rating between high and low arch.
- ***Foot sensitivity:*** Subjects with a low tactile sensitivity at the heel, the medial arch and the first metatarsal head showed a preference for high arch inserts (Figure 43). This result was confirmed for only the medial arch in the group comparison of the comfort rating between high and low arch (Figure 44).

Synthesis:
Most subjects preferred the high arch inserts over the low arch ones. A combination of several factors may have been the reason for this choice.
First, the fit between shoe and foot may have played a role. Subjects with a loose fit do not receive any support from the forefoot area and need, therefore, support from somewhere else. This missing support may have been provided by the foot arch.
Second, a high arch insert may be important to support subjects with a low arch. However, subjects with a high arch, which is often also a stiff arch, may not require additional support. Thus, subjects with a high arch showed no preference.
Third, the alignment of the foot and leg may have played a role. Subjects with a well aligned foot and/or leg (low Q-angle and low beta) preferred the high arch inserts. This was not true for subjects with a poorly aligned foot and/or leg. Increased height of the arch support may increase the risk of malaligment.

Finally, foot sensitivity was an important factor. For those subjects that had less sensitive heels, medial arches and first metatarsal heads, high arch inserts were preferred. This may have been related to the pressure on the plantar surface of the foot. It was observed that the peak pressure at the mid-foot and hallux was higher for the high arch insert than the low arch insert (Figure 28). Insensitive subjects might have required the increased peripheral input provided by the high arch inserts.

GENERAL RESULT	High arch preferred over low arch	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
FOREFOOT WIDTH	Tight fit preferred low arch	
ARCH HEIGHT	Low arch foot preferred high arch insert	
Q-ANGLE	High Q-angle preferred low arch	Subjects who preferred low arch had a higher Q-angle
SUBTALAR ALIGNMENT	Poorly aligned subtalar joint preferred low arch	
FOOT SENSITIVITY	Less sensitive (tactile) heel, medial arch and first metatarsal head preferred high arch	Subjects who preferred high arch insert had a sensitive medial arch (tactile)

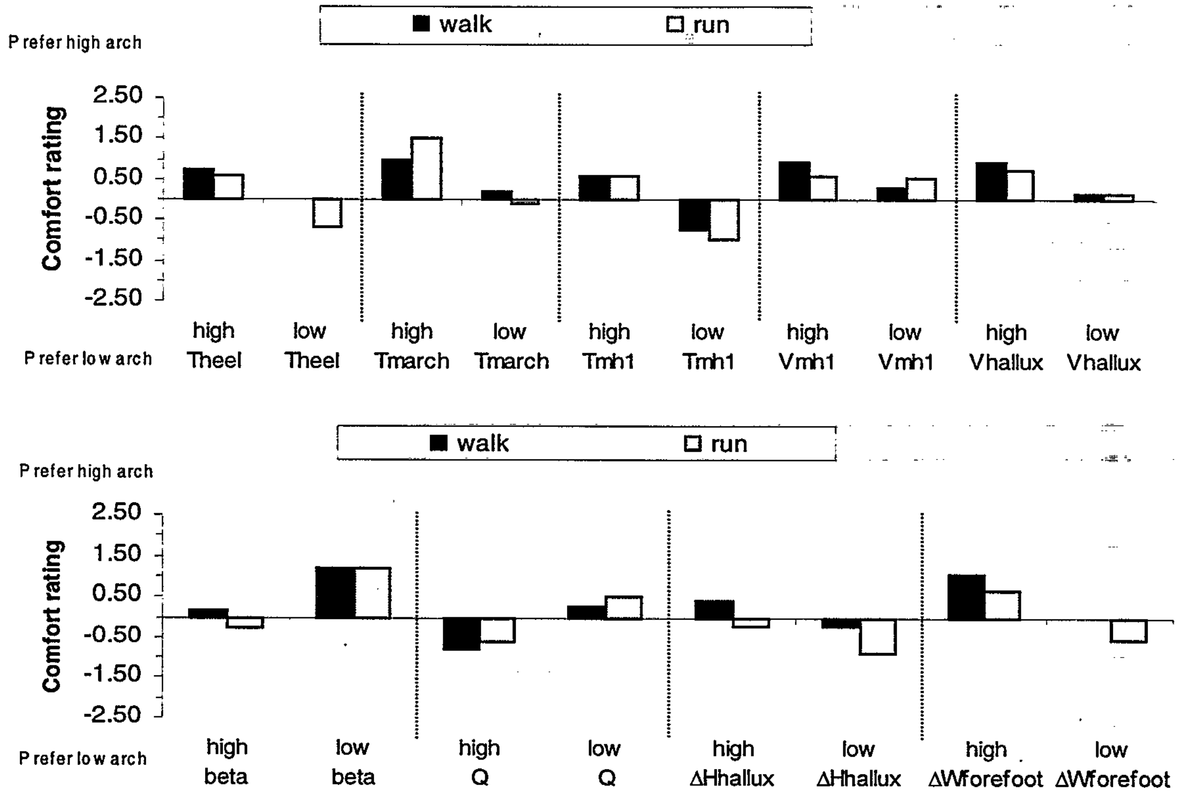


Figure 43. Comparison of differences in comfort ratings between a high arch (insert #4) and a low arch (insert #5) insert for subject groups divided according to foot characteristics.

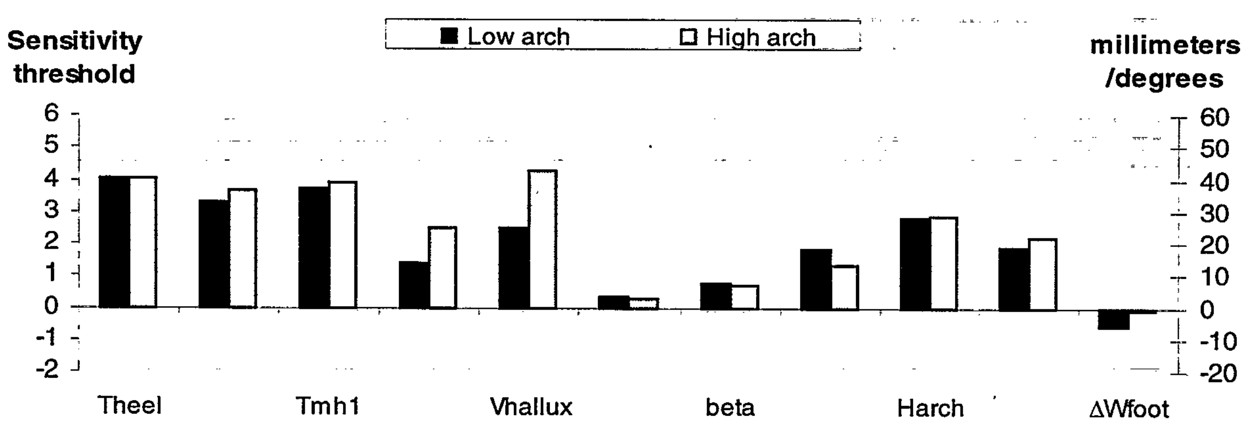


Figure 44. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between a high arch (insert #4) and a low arch (insert #5) insert.

5) Viscous forefoot – Elastic forefoot (soft materials):
#3 – #4

General results:
In general, the test subjects preferred the elastic over the viscous insert. On average the elastic insert was rated 0.63 comfort points higher for walking and 0.42 comfort points higher for running.

Specific results:

- ***Hallux height:*** Subjects with a high difference between the hallux heights of shoe and foot (a loose fit of the shoe around the hallux) made no preference for either insert. However, subjects with a tight fit at the hallux preferred elastic insert (Figure 41). This result was not confirmed in the group comparison of the comfort rating between viscous and elastic.
- ***Q-angle:*** Subjects with a high Q-angle preferred the viscous insert. However, subjects with a low Q-angle preferred the elastic insert (Figure 41). This result was confirmed in the group comparison of the comfort rating between viscous and elastic (Figure 42).
- ***Subtalar alignment:*** Subjects with a well-aligned subtalar joint (low beta) preferred the elastic inserts. Subjects with a poorly aligned subtalar joint (high beta) made no preference (Figure 41). This result was not confirmed in the group comparison of the comfort rating between viscous and elastic.
- ***Foot sensitivity:*** Subjects with high tactile sensitivity at the first metatarsal head showed a preference for viscous inserts. However, subjects with low tactile sensitivity at the first metatarsal head preferred the elastic inserts (2.5 comfort points difference for walking and running) (Figure 41). Subjects with a high tactile sensitivity at the 5th metatarsal head made no preference while subjects with low tactile sensitivity were in favour of elastic inserts. Both results were confirmed in the group comparison of the comfort rating between viscous and elastic (Figure 42).

Synthesis:
Most subjects preferred the elastic inserts over the viscous ones. A combination of several factors may have been the reason for this choice.
First, the available space between foot and shoe may have played a role. For the hallux, tightness has produced increased pressure (Fig. 31). A possible reason for this preference is not obvious at this point in time.
Second, the alignment of the foot and leg may have played a role. Subjects with good alignment (low Q-angle and low beta) preferred the elastic inserts. Subjects with poor alignment (high Q-angle) preferred the viscous inserts. It may be that the viscous inserts may reduce the amount of movement, and therefore limit the risk of further malalignment. Thus, the speculation that subjects with possible malalignment in the skeleton prefer viscous inserts was confirmed.
The strongest factor in the selection of elastic over viscous was the foot sensitivity. Subjects that were more sensitive at the first and 5th metatarsal heads favored viscous over elastic inserts. A possible explanation for this result is that the movement of the forefoot inside the shoe may be

restrained during walking and/or running with a viscous insert. Excessive movement at the forefoot may be uncomfortable for the sensitive subjects.

In summary, elastic forefeet were generally preferred over viscous forefeet. Viscous forefeet were only preferred for subjects with problems in the alignment of their skeletons.

GENERAL RESULT	Elastic preferred over viscous	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
HALLUX HEIGHT	Tight fit preferred elastic	
Q-ANGLE	High Q-angle preferred viscous Low Q-angle preferred elastic	Subjects who preferred viscous had a higher Q-angle Subjects who preferred elastic had a lower Q-angle
SUBTALAR ALIGNMENT	Well aligned subtalar joint preferred elastic	
FOOT SENSITIVITY	Highly sensitive (tactile) first metatarsal head preferred viscous Less sensitive (tactile) 5th metatarsal head preferred elastic	Subjects who preferred viscous had a sensitive first metatarsal head (tactile) Subjects who preferred elastic had less sensitive 5th metatarsal head (tactile)

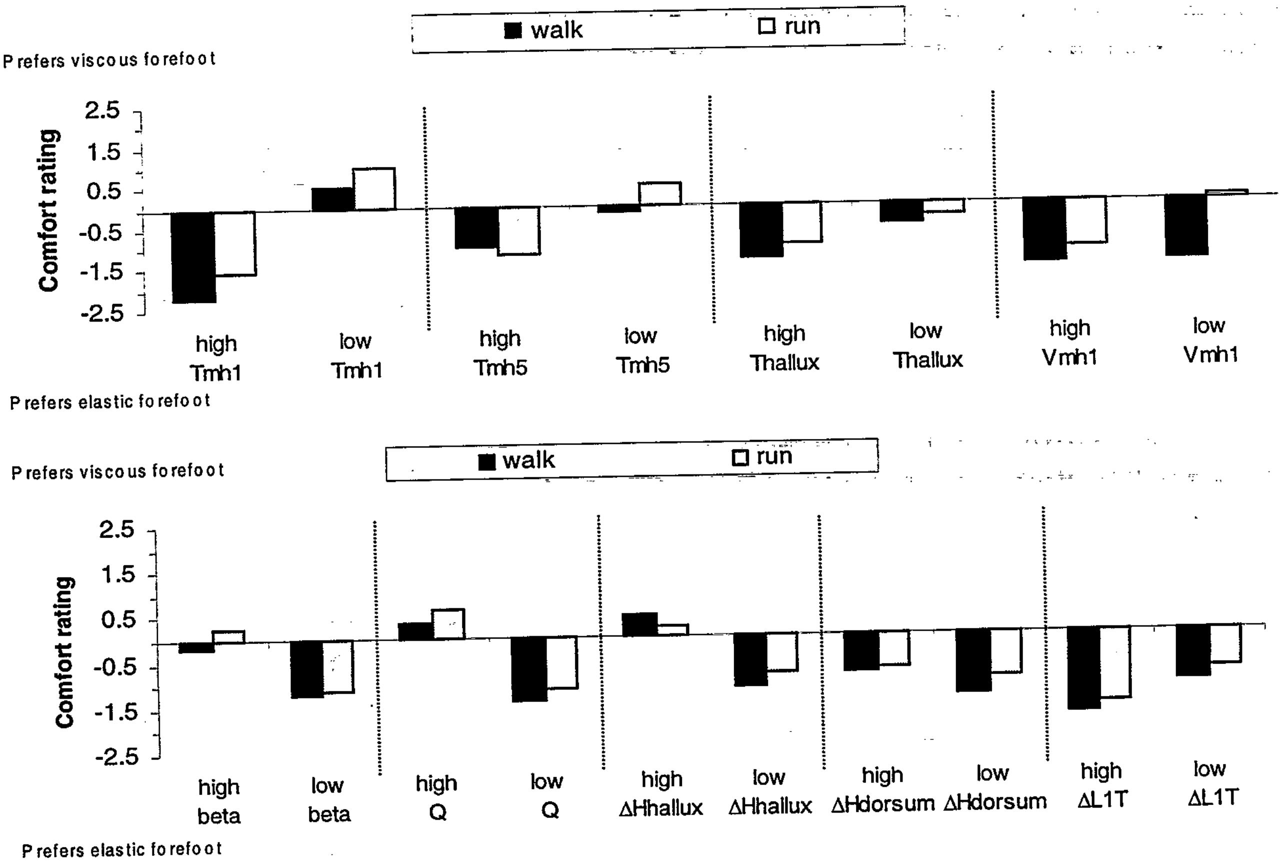


Figure 41. Comparison of differences in comfort ratings between a viscous forefoot (insert #3) and an elastic forefoot (insert #4) for subject groups divided according to foot characteristics.

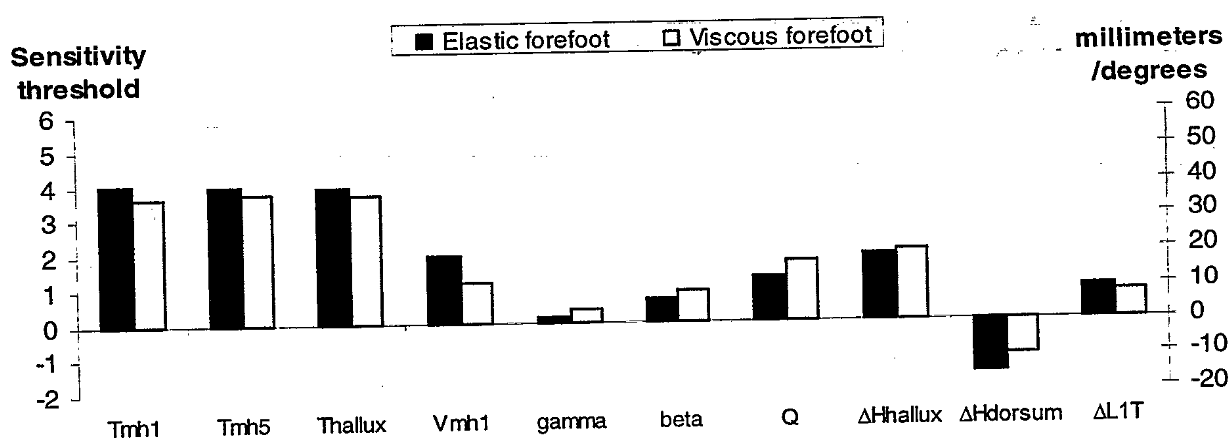


Figure 42. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between a viscous forefoot (insert #3) and an elastic forefoot (insert #4).

6) Hard elastic – soft viscous (whole insert): #1 – #3

General results:
In general, there was no preference for either insert. The average rating for the hard, elastic insert was 6.77 and 6.49 for walking and running, while for the soft, viscous insert the ratings was 6.61 for both walking and running.

Specific results:

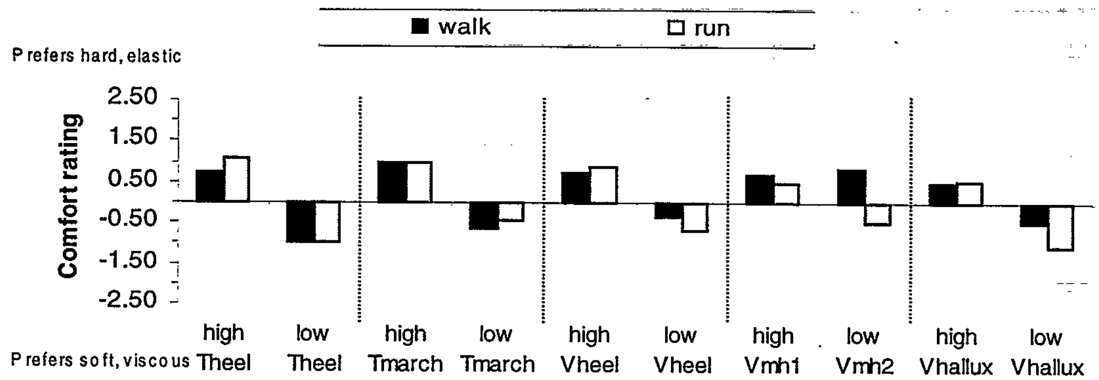
- ***Heel width:*** Subjects with a small difference between the width of the shoe heel and the width of the heel of the foot, ΔW(heel), strongly preferred the hard, elastic insert. Those with a large difference in heel width between the boot and foot, a loose fit, did not make a preference for either insert (Figure 39). These results were not supported when the subjects were grouped according to comfort ratings of the two inserts (Figure 40).
- ***Hallux height:*** Subjects with a high difference between the hallux heights of shoe and foot (a loose fit of the shoe around the hallux) did not distinguish between either insert. However, subjects with a tight fit at the hallux preferred a soft, viscous insert (Figure 39). This result was not confirmed in the group comparison of the comfort rating between hard, elastic and soft, viscous inserts (Figure 40).
- ***Foot sensitivity:*** Subjects with a high tactile and vibration sensitivity at the heel preferred the soft, viscous insert. Those with low tactile and vibration sensitivity at the heel rated the hard, elastic insert as more comfortable (Figure 39). The difference between the two groups was approximately 1.5 comfort points. These results were confirmed when the subjects were grouped by comfort rating. Subjects who preferred the soft, viscous insert were more sensitive at the heel to both tactile and vibration stimuli (Figure 40). Subjects with a highly sensitive medial arch to tactile stimuli preferred the soft, viscous insert while subjects with a less sensitive medial arch preferred the hard, elastic insert. Subjects with greater sensitivity at the hallux to vibration stimuli also preferred the soft, viscous insert (Figure 39). Again, these results were supported by the group comparisons of insert comfort rating. Subjects who preferred the soft, viscous insert were more sensitive to vibration stimuli at the hallux (Figure 40).

Synthesis:
In general, there was no overall preference for either the hard-elastic or the soft-viscous inserts. However, a strong pattern emerged between the different subgroups that showed differences in comfort rating based on several anthropometric and sensitivity variables.
First, for subjects with a tight fit at the heel (low ΔWheel), a strong preference was made for the hard insert. A hard insert may reduce the amount of abrasive micro-movements at the heel, and reduce the stress placed on the skin around the heel. For subjects with a tight fit at the hallux, a preference was made for a soft, viscous insert. For the hallux, tightness produced increased

pressure (Figure. 23). Thus, if there is not enough space (tight fit), a soft insert may have allowed an easier adjustment.

The sensitivity of the foot was of major importance in determining the comfort level of the two inserts. Subjects with highly sensitive feet to both tactile and vibration stimuli strongly preferred the soft, viscous insert. The opposite was true for the subjects with low sensitivity. A possible explanation for this result could be that the soft, viscous material increased the contact area of the foot, and hence reduced the pressure under the foot. Pressures at the hallux were lower for the soft viscous insert (#3) compared to the hard elastic insert (#1) (Figure 23). A soft, viscous insert was assumed to reduce both the frequency and amplitude of the input signal. For subjects with highly sensitive feet, this would, therefore, be more comfortable.

GENERAL RESULT	No overall preference for either insert	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
HEEL WIDTH	Tight fit preferred hard, elastic insert	
HALLUX HEIGHT	Tight fit preferred soft, viscous insert	
FOOT SENSITIVITY	Sensitive heel (tactile and vibration) preferred soft, viscous insert Low sensitivity at heel (tactile and vibration) preferred hard, elastic insert	Subjects who preferred soft, viscous insert were more sensitive at heel (tactile and vibration) Subjects who preferred hard, elastic insert were less sensitive at heel (tactile and vibration)
	Sensitive medial arch (tactile) preferred soft, viscous	
	Sensitive hallux (vibration) preferred soft, viscous	Subjects who preferred soft, viscous insert were more sensitive at hallux



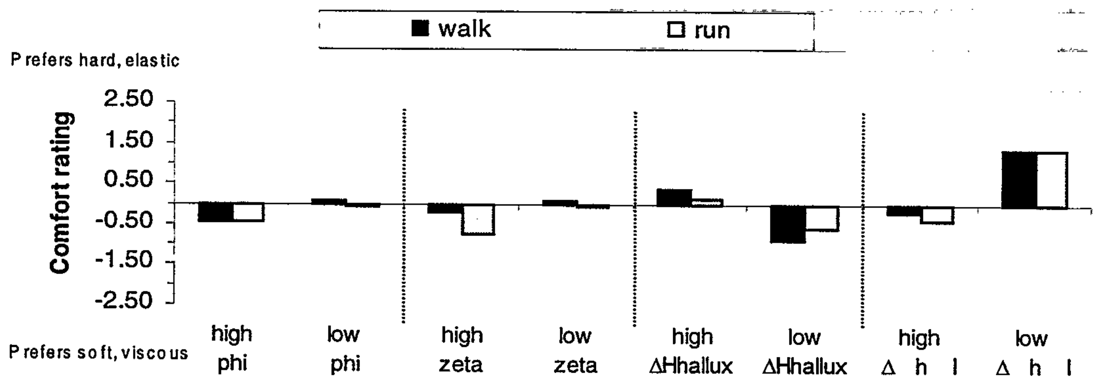


Figure 39. Comparison of differences in comfort ratings between hard elastic (insert #1) and soft viscous (insert #3) inserts for subject groups divided according to foot characteristics.

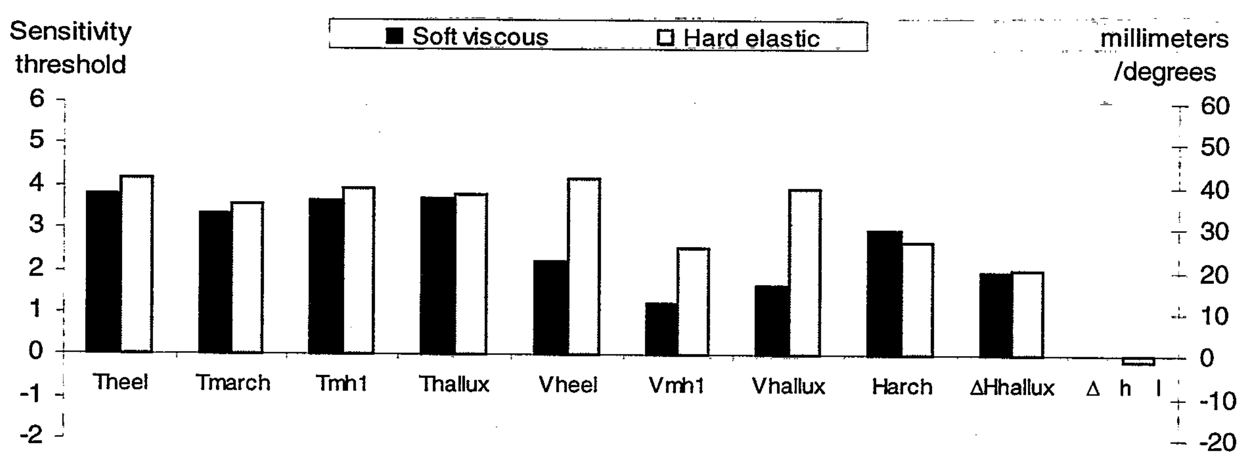


Figure 40. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between the hard elastic (insert #1) and soft viscous (insert #2) inserts.

7) Soft medial, hard lateral forefoot – hard medial, soft lateral forefoot: #6 – #7

General results:
In general, there was no difference in the overall comfort rating between the two inserts. For both running and walking the difference in comfort rating was less than 0.1.

Specific results:

- ***Dorsum height:*** Subjects with a small difference between the height of the dorsum of the foot and boot (ΔH_{dorsum}), which corresponds to a snug fit at the dorsum, preferred a soft medial forefoot (Figure 49). This result was not confirmed in the group comparison of the comfort rating between forefoot differences (Figure 50).
- ***Arch height:*** Subjects with a high arch preferred a soft medial forefoot while subjects with a low arch preferred a soft lateral forefoot. This result was not confirmed in the group comparison of the comfort rating between forefoot differences.
- ***Foot sensitivity:*** Subjects with higher tactile sensitivity at the fifth metatarsal head made a strong preference for a soft lateral forefoot. Subjects who were less sensitive had no preference for either insert. This result was not confirmed in the group comparison of the comfort rating between forefoot differences.

Synthesis:
There was no general trend regarding the preference of either a soft medial or soft lateral forefoot. All findings for the different variable groups were not confirmed in the general assessment comparison.
Subjects with a high arch or tight fit at the dorsum preferred a soft medial forefoot. Thus, if there is not enough space (tight fit), a soft insert may have allowed an easier adjustment.
Subjects with high tactile sensitivity at the fifth metatarsal head preferred a soft lateral forefoot. Soft inserts are assumed to reduce amplitude and frequency of the input signals. Subjects that are highly sensitive would, therefore, consider such soft inserts as more comfortable.

GENERAL RESULT	No preference between soft medial and soft lateral forefoot	
FACTORS	**COMPARISON FOOT CHARACTERISTICS**	**COMPARISON COMFORT RATING**
DORSUM HEIGHT	Tight fit prefer soft medial forefoot	
ARCH HEIGHT	High arch prefer soft medial forefoot	
FOOT SENSITIVITY	High sensitivity (tactile) at the fifth metatarsal head prefer soft lateral forefoot	

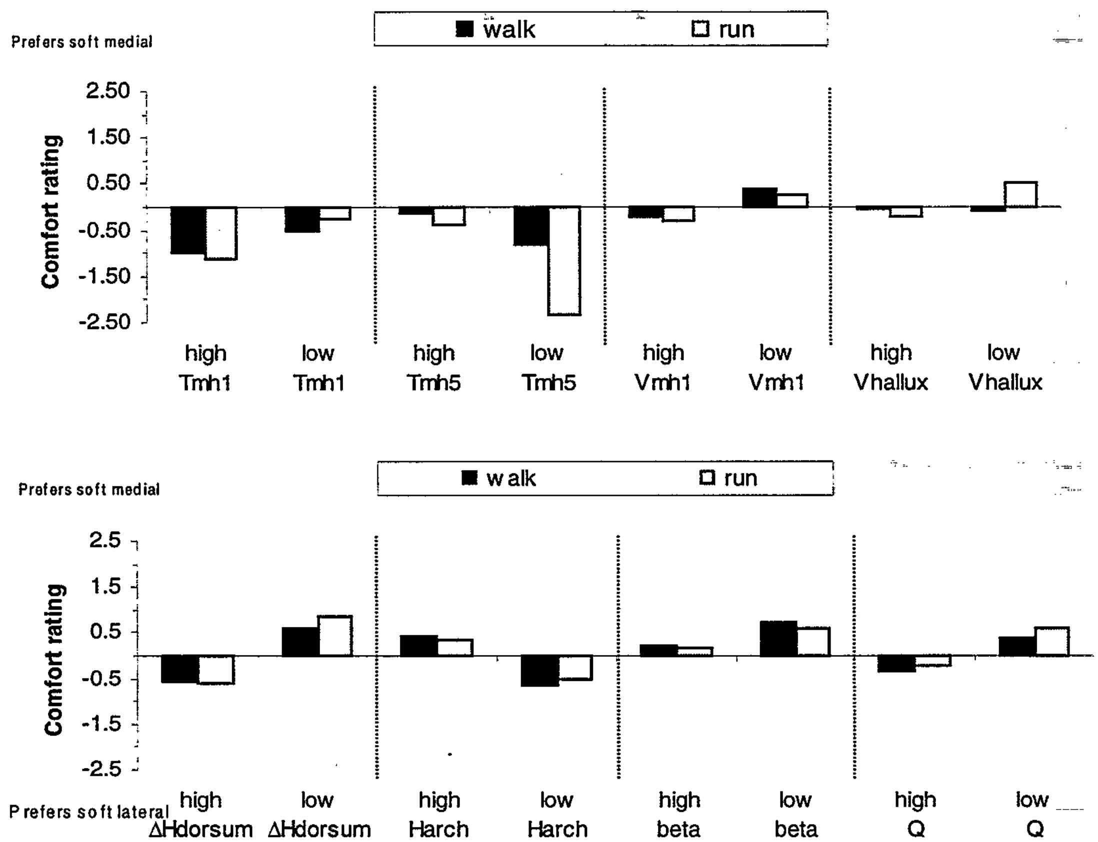


Figure 49. Comparison of differences in comfort ratings between a soft medial forefoot (insert #6) and a soft lateral forefoot (insert #7) for subject groups divided according to foot characteristics.

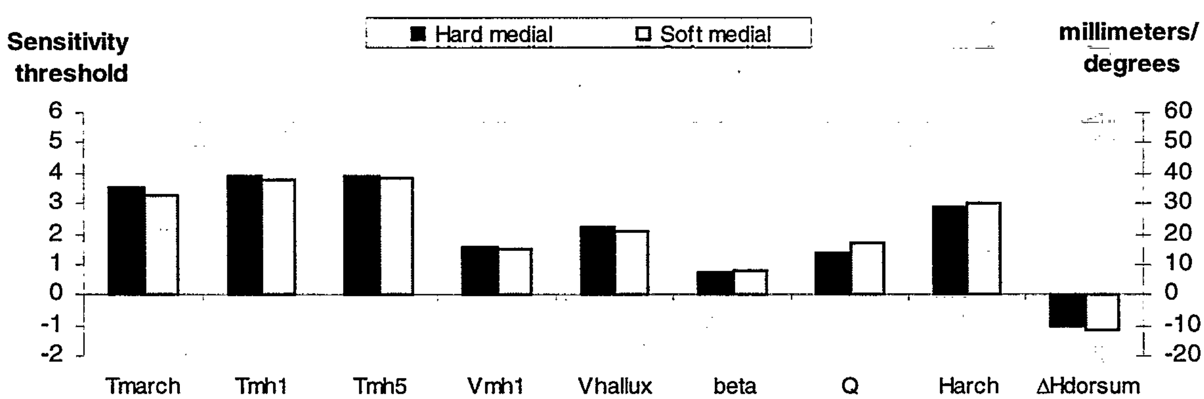


Figure 50. Comparison of differences in foot characteristics for the group of subjects with the largest difference in comfort ratings between the soft medial forefoot (insert #6) and the soft lateral forefoot (insert #2).

Specific insert results

The specific results can be summarized as indicated in Table 16.

Table 16. Summary of the results for the shoe-foot characteristics as they relate to the insert characteristics.

COMPARISON		Soft – #2	Hard #1	Visc. – Heel #8 #4	Elas. Heel #9 #2	Spher. – Heel #2 #4	Flat Heel #9 #8	High – Arch #4	Low Arch #5	Visc. – Fore. #3	Elas. Fore. #4
Average Comfort		■			▒	■		▒			■
FIT											
Arch	High				▒	▒					
	Low							▒			
Heel	Loose				▒						
	Tight		▒				▒				
Toe	Loose										
	Tight	▒							▒		▒
ALIGNMENT											
Heel	Good										
	Poor	▒									
Subtalar	Good										▒
	Poor				▒				▒		
Tibial	Good										
Torsion	Poor			■							
Q-angle	Good										■
	Poor				■				■	■	
SENSITIVITY											
Tactile	High	■			▒						
Heel	Low							▒			
Tactile	High					▒					
Arch	Low				▒		▒	■			
Tactile	High										
Hallux	Low										
Tactile	High									■	
Met. heads	Low					▒		▒			■
Vibration	High	■			▒	▒					
Heel	Low										
Vibration	High	■		■							
Hallux	Low										
Vibration	High			■							
Met. heads	Low					▒					

■ Indicates a strong preference

▒ Indicates a weak preference

The insert characteristics of importance throughout the study for high comfort assessment were

- soft material properties,
- spherical heel and
- an elastic forefoot material.

In addition to these preferred characteristics

- the elastic heel was slightly preferred over the viscous heel and
- the high arch was slightly preferred over the low arch.

However, these latter two variables (visco-elasticity of the heel and arch height) were not as important as the primary variables (soft insert material, spherical heel and elastic forefoot material) in terms of preference by the subjects. Visco-elasticity of the heel and arch height are variables that seem not as important. It is speculated that good results for large subject groups can be achieved with viscous or elastic heels and with high or flat arch supports.

However, there are certain foot/shoe characteristics that do not fit into this general solution. Whenever the heel fit is tight, the hard material is preferred over the soft material. However, selecting a wider heel insert can solve this problem. Based on the results of this study, there is no reason to prefer hard over soft.

The viscous heel was preferred by the subjects with a tight heel fit, substantial tibial-rotation and high vibration sensitivity of the hallux. At this point in time, there is no obvious criterion for this grouping of subjects that prefer viscous heels.

The two confirmed factors that preferred elastic heels were poor subtalar joint alignment and good [straight] Q-angle. Again, there is no obvious pattern for this grouping. This leads to the suggestion that the variables that have been shown as different for the different heel materials should be studied further. At this point in time, the conclusion would be that both solutions (elastic and viscous heels) are acceptable.

The spherical heel was clearly preferred over the flat heel. There were only a few, not confirmed factors, which suggested that the flat heel may be more advantageous, however, based on the results of this study the spherical heel is the preferred choice for an insert.

With respect to the arch in the insert, subjects generally preferred an arch. However, there were two groups, which did not agree with that assessment. Subjects with a poor Q-angle and subjects with a poor subtalar joint alignment were those, which preferred a low arch. That could be interpreted as an indication that poor joint alignment is associated with the preference of low insert arches.

The material property of choice for the forefoot was elastic. However, subjects with two specific characteristics preferred viscous forefoot material. Subjects with a bad Q-angle and subjects with a high tactile sensitivity at the metatarsal heads preferred viscous forefoot materials. If one compares this with the fact that viscous forefoot materials demand about 1 to 2% more energy during locomotion one should avoid viscous materials for the forefoot except for specific sub-groups (high Q-angle and high tactile sensitivity at the metatarsal heads). It is interesting, however, in this context that the opposite groups, those with the good Q-angle and those with the low tactile sensitivity at the metatarsal heads had just the opposite preferences, they preferred elastic forefoot materials.

Speculation-Concepts

In the attempt to group the results to formulate speculations for future research and appropriate insert construction, the following concept/speculations can be made:

1. If subjects have a poor alignment of the skeleton (heel, subtalar joint, tibial torsion, Q-angle) they are best served with a soft and viscous insert with no medial arch support. This statement is supported by 5 out of 6 results in the summary table. The statement about soft material and low arch seems to be strong, the statement about viscous material is less strong. In support of this speculation one could argue that people with poor skeletal alignment do not want anything resisting their foot movement. Thus, they prefer soft and viscous materials with no arch support.

2. Subjects that are highly sensitive (tactile and vibration) prefer soft and viscous materials. Subjects that have a low sensitivity (tactile and vibration) prefer elastic materials and a high arch. These are two strong speculations, which can be supported by functional considerations. Subjects who are highly sensitive don't need extra input signals. However, subjects who are not highly sensitive may need strong input signals (produced by the elastic material and the high arch).

The variables describing the shoe fit showed results, which in some cases corresponded to strong preferences for specific constructions. Problems created by too loose or too tight fit in the heel or at the toe, however, are subject specific and can be resolved by changing the shoe (e.g. by choosing a bigger size). They should not and did not provide any systematic results that can be explained functionally. Thus, they should not be considered further as determining variables. However, they should be included as constraint variables for further studies.

The first step in the program to determine factors important for footwear of military personnel has shown some interesting results and resulted in some strong speculations for grouping of shoe-foot characteristics. The next step should include dynamic and long-term experiments in which specific speculations and hypotheses are tested.

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