THE UNIVERSITY OF CALGARY

THE CORRELATION BETWEEN PLANTAR PRESSURE DISTRIBUTION AND SHOE COMFORT

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled, "The Correlation Between Plantar Pressure Distribution and Shoe Comfort", submitted by Heli Chen in partial fulfillment of the requirements for the degree of Master of Science.

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ABSTRACT

Comfort is an important aspect in shoe design and shoe manufacture. However, certain criteria have to be determined for shoe comfort. Comfort cannot be measured directly, but some measurable variables may be used to interpret comfort. In this thesis, plantar pressure distribution was used to study comfort. In comparison with less comfortable shoe, the comfortable shoe produced lower pressure and provided an even distribution of the pressure at the plantar surface of the foot. The nervous system plays an important role in comfort. To test the sensory aspect of comfort, plantar pressure distribution was compared between presummed increased sensory input and normal conditions. The increased sensory input caused discomfort and produced high pressure at the plantar surface of the foot. In general, pressure measurement can indicate the changes of comfort and sensory conditions and may be used in definition of comfort.

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To

My Family

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CHAPTER 1

INTRODUCTION

Wearing a pair of "sporty" comfortable shoes with an "athletic look" has become fashion in the last 20 years and made sport shoes an important market for shoe manufactures. A 1983 shoe survey in the U.S. found that 36.9% of men's footwear purchases were sport shoes [17], and this figure seems to be continuously increasing in the recent years. With the development of sport shoe design and marketing, comfort became an increasingly important aspect for consumers to buy sport shoes [11] [17] [51]. In a 1978 American national consumer survey and in a 1974 French footwear survey, comfort and fit (physical and anatomical aspects of comfort) ranked number one in a consumer preference list when purchasing regular sport footwear [17].

In contrast to factors such as impact forces or flexibility of shoes, which can be measured directly, comfort is a kind of subjective feeling depending on individual differences and cannot be measured directly [11]. Comfort survey based on questionnaires about shoes may be a good help to provide general ideas on shoe comfort and scale the comfort level of shoes. However, for understanding the feeling of comfort, it can be of more importance to know why and how the human body is reacting to different stimuli such as impact and pressure. These factors may be related to quantitative approaches to evaluate shoe comfort [29] [40] [83]. On the other hand, it is very difficult to measure the effect of physical variables on the feeling of comfort. To author's knowledge, no studies are available about the nature of the scale in which comfort can be measured. One way to gain insight into the complex area of shoe comfort is to find possible factors which may influence the feeling of comfort, and try to understand the relation between the measurable physical factors or phenomena associated with these factors and the feeling of comfort.

Selected shoe characteristics can influence the movement of the athlete's body during running and walking, and provide changes in the mechanics and kinetics of the body which could effect the feeling of comfort. Pressure distribution between the plantar surface of the foot and the shoe during running and walking may be one possible factors influencing the feeling of comfort.

Pressure distribution under the foot was widely used in studies on foot type classification, gait analysis, foot orthopaedic, shoe type test, and barefoot and shod walking patterns [10] [13] [22] [39] [58] [66]. Previous studies on the pressure distribution of the foot showed that pressure information was an effective quantitative factor to illustrate the mechanical reaction of the human body to the change of foot environment. In a pilot study on shoe comfort, the pressure distribution was compared between comfortable shoes and less comfortable shoes [29]. Significant differences in force and pressure were found in the midfoot area and at the heel between comfortable and less comfortable shoe conditions. This pilot study showed that the maximal force in the midfoot area and the peak pressure at the heel was higher for the less comfortable than for the comfortable shoe, and that the midfoot contact area was greater for the less comfortable shoe. The results of this study suggests that pressure distribution under the foot can provide useful information about shoe comfort and may be applicable for the assessment and quantification of comfort.

The feeling of comfort is related to the sensory feedback system of the human body. The pressure distribution of the foot may connect the sensory function of the foot to comfort.

The purpose of this study is a) to investigate the relationship between plantar pressure distribution of the foot (a quantitative variable) and running shoe comfort (a qualitative variable), b) to investigate the relationship between plantar pressure distribution of the foot and sensory inputs, and c) to decide how the pressure pattern for comfort may relate to sensory feedback.

In this project, firstly, two pressure measurement systems: Fscan and EMED were tested and compared. Secondly, pressure distribution was investigated under comfortable and less comfortable running shoe conditions to study if there exists a special pressure pattern for comfortable shoes. Thirdly, pressure distribution was investigated under different conditions of sensory input. Furthermore, the pressure patterns for comfort and sensory input were compared to show the connection between comfort and sensory feedback.

CHAPTER 2

LITERATURE REVIEW

The primary goal of this study is to investigate the relationship between the pressure distribution of the foot and shoe comfort. The literature reviewed in this part will divided into two sections: comfort and pressure distribution measurement.

2.1 COMFORT

A person can easily determine whether or not a shoe feels comfortable. What, then, is comfort? How is comfort defined? Comfort may be described as a subjective feeling. However, comfort has been defined in many different ways. Comfort is a pleasant state of psychological, physiological and physical harmony between a human being and the environment. Comfort is the sense of what feels good [30] [74]. Comfort may be defined as "a state or feeling of having relief, encouragement, or consolation... physical or mental well being, especially in freedom from want, anxiety, pain or trouble..." (Webster's 1959); Comfort "(of mental sensations and conditions) is consolation in sorrow, anxiety, relief from sorrow...; (of physical sensations and conditions) bodily ease, well being, repose; freedom, relief from pain... ease of circumstances, pleasant, cheerful, sheltered condition of life, sufficiency, luxury..." (Wyld, 1961). Overall, comfort is a pleasant state of psychological, physiological and physical harmony between a human being and the environment [74]. These descriptions include all the aspects of the comfort: psychological, physiological, physical and environment factors.

2.1.1 Psychological Aspects of Comfort

Psychological comfort is the feeling of consolation, contentedness, peace [24] and is a kind of satisfaction and pleasantness in mind [74].This feeling mostly depends on the individual: his self-image, personal state, adaptation and agreement to the environment, his physical condition as well as the relationships between the individual, other human being, and the society. In the same external condition, different persons could have different feeling of comfort. Even for same person, the feeling of comfort could be different at the different times. Depression, anxiety, worry, want, pain, or unpleasantness are usually used to describe a discomfort state of the mental kind and measure the comfort level of the individual [8] [24] [74].

2.1.2 Physiological Aspects of Comfort

Physiological comfort can be identified in all parts of the body and in virtually all of its mechanisms. The cardiovascular system, the musculo-skeleral system, the central nervous system, the pulmonary system, the digestive system, the sensory faculties, and the thermoregulatory mechanism are all involved in some way with the body' s continual attempt to become more comfortable. The basic requirements for the comfort are the keeping of the basic balance and normal work state of the systems (disease-free or health) and the meeting of the bodily needs such as sufficient (but not too much) food, oxygen, heat energy, etc [74].

The nervous system plays an important role in comfort. Through the nerves, external signals (stimuli) such as sound, smell, light, food, heat, touch, pressure acted on the related organs (ears, nose, eyes, tongue, skin respectively) are sent to the brain, the sensory and control centre of the body, and produce the sense of hearing, smell, sight, taste, heat, touch and pain, etc [81]. When some part (or system) of the body is in disorder, some signs such as pain, fever... could be indicated through the sensory system and cause a feeling of discomfort [74].

The comfort level usually depends on not only the intensity of the stimulus from outside or inside body, but also the sensitivity of the sense of an individual as well as the experience. Person who has higher sensitivity may feel discomfort by stimulation, while other people feel comfort in the same condition. A pleasant sensory experience can increase the comfort level. On the other hand, an unpleasant sensation can destroy the feeling of comfort. However, adaptation to the stimulus could change the comfort state: discomfort can be changed into comfort [8] [74].

2.1.3 Physical Aspects of Comfort

Physical comfort is a state in which the basic physiological requirements of survival have been met and physiological homeostasis is maintained [23]. In many ways it is more tangible for person through perception of sensation. It is related directly to either the physiological or psychological forms of comfort when we begin to notice the problems of physical comfort. The physical comfort level has great effects on the physiological or psychological comfort level [74].

There are close relationships between the three aspects of comfort that have been described above [23] [24] [74]. Physical pain could effect the individual' s emotional condition such as depression, anxiety, etc., then, effect on his physiological system, and finally, aggravate the pain. A pleasant or relaxed (comfortable) state in psychology may relief from or reduce the discomfort (e.g. pain) of the body. In many ways, Improving physical comfort level can improve both comfort levels in physiology and psychology. That is one of reasons why excise and fitness is becoming more and more popular. On the other hand, comfort is relative. It is possible for a person suffering physical pain (discomfort) feeling comfort in mental kind. If the pursuing for psychological comfort is more important, one could discard or ignore the physical comfort (Is it comfortable wearing high-heeled shoes?).

2.1.4 Comfort and Safety

Safety is an important factor of comfort. The minimal requirements for comfort and safety are: to be free from physical injuries, to have protection from the external environmental causes of illness and disease, to be safe from pathogenic organisms, and to be from pain and hungry [23]. However, the feeling of comfort can also be counter-productive for the safety. Robbins and coworkers have suggested that shoes with high plantar comfort may produce a perceptual illusion of small impact forces. This illusion they suggested leads to an inefficient impact-moderating running style and can produce chronic overloading injuries [61].

2.1.5 Measurement of Comfort

Psychological factors related comfort may be assessed subjectively [74]. A "discomfort threshold" is often used as a variable to assess comfort psychologically. It is a mean of expressing that discomfort is not experienced until it gets large enough to be brought to subjects' attention or perception. In this case, comfort can be described as "minimal discomfort", or "minimal tolerant discomfort" [4] [38].

Some factors related to comfort or discomfort can be measured objectively. Magnitude of pressure in an above-knee socket was measured to provide an information of comfortable socket [40]. In Nowroozi and Salvanelli's study, the lowest energy cost was measured and demonstrated a comfortable walking speed [55].

2.1.6 Comfort In Footwear

When focusing on the shoe comfort, the question arises how a pair of shoes can be evaluated as being comfortable. There are many important factors in shoe comfort:

1. **Style** Some buyers of sport shoes pursue fashion for psychological comfort. Style and colour of shoes may be the first consideration for a consumer to buy a pair of shoes [17].

2. **Shoe fit** Fit is an important factor for shoe comfort [11] [44] [51]. A shoe that fits badly is uncomfortable. More comfort and better performance can be obtained, when the dimensional profile and sections of the shoe correspond to the dimensional profile and sections of the foot. The most important element in shoe fit is the shoe size and shape, which is determined by the last [11] [44] [69]. Battell Memorial Institute gave 37 factors that influence the fit of shoe. The factors involved not only obvious factors such as materials, last, size, heel height, construction (for physical fit), etc., but a variety of emotional and psychological factors such as shoe style, colour, brand, price, consumer opinions on fit [17] [69].

3. **Protection and relief from pain and injury** Pain and injury produced by shoes is not only uncomfortable, but also influences performance. In order to avoid pain and injury, there are several biomechanical properties that a shoe should satisfy:

   - A shoe sole having a good shock absorbing function [11] [18] [20] [43] [51] [80] and producing minimal pressure or load between foot and insole [11] [43] [71] [80].

   - Reduction of friction or shear force between the planter and insole. The friction from the movement between foot and shoe is a barrier to comfort, particularly on the sole. Blusters and calluses are primarily caused by excessive shear forces referred to as friction, acting on the skin [78].

   - Sufficient flexibility on the sole. A rigid sole will not only limit the movement of the foot, but also produce large forces on the foot to cause pain or even injury [11] [45]

- A pair of comfortable shoes should have sufficient thermal insulation but produce minimal perspiration from the feet [11].

According to the hypothesis stated by Frederick [25], comfort is a multivariate phenomenon which is a function of three primary factors:

1. **maintaining a suitable micro-environment.** If a shoe design has sufficient environmental controls to regulate in-shoe climate within a specified range while it is being used in normal ambient conditions, it will be perceived as comfortable.
2. **the absence of irritation.** If a shoe design does not produce local irritations to the foot, then the shoe will be perceived as comfortable.
3. **maintaining localized pressure below threshold values.** If a shoe design maintains pressures, both plantar and non plantar between the foot and the shoe below threshold values then the shoe will be perceived as comfortable.

2.2 PRESSURE DISTRIBUTION MEASUREMENT

2.2.1 Development of Measurement Techniques

Earliest attempts to quantify force distribution started at the end of the 19th century. In 1882, Beely made the first recorded pressure measurements by having subjects standing on a sack of plaster of Paris and relating depths of indentations to the maximal local forces. Abramson, in 1927, used steel shot underneath a soft lead sheet to measure pressure distribution [22].

Morton (1930) utilized a rubber mat with longitudinal ridges on top of an inked ribbon to measure the pressure under the foot [46]. The width of the lines was proportional to the maximal local forces. Morton related certain aspects of the kinetochores to the radiologically observed foot abnormalities. His study showed a high concentration of pressure under the second metatarsal head in subjects with a short first metatarsal (the infamous Morton' s toe). In generally, those who did not show this characteristic exhibited an even spread of pressure.

Elftman (1934) was the first to successfully record instantaneous pressure distribution [22]. He used a rubber mat with pyramidal projects on its undersheriff mounted on a rigid glass plate with reflecting fluid in the spaces between the mat and the glass plate. The deformation of the rubber pyramids was filmed to provide information on the dynamic force distribution. He investigated three problems: the change in pressure distribution during normal steps, the effect of foot anatomy on the position of the applied forces, and the influence of foot posture on the distribution of forces under the foot. The result of his study showed that forces, from heel impact to toe-off, gradually increased through the course of a normal step. The structure of the foot influenced the position of the force application by equalizing the distribution under the entire foot. Abduction and adduction also influenced the region under the foot which received the greatest amount of force. In conclusion, Elftman claimed that the line from the point with greatest heel pressure to the point with greatest forefoot pressure was parallel to the direction of movement.

Barnett (1954) applied his "plastic pedobarograph" device with 640 transparent rods vertically mounted on a rubber support for the pressure measuring [5]. As a subject walked across the rods, the depression of a given position along one horizontal line of the graph was proportional to all the horizontal lines. The movement of the rods was filmed to determine the dynamic force distribution.

In 1963, Bauman described a method using single capacitive force transducers for measuring selected local force between foot and shoe [7]. The transducer was a 1 mm capacitor with a 1 cm^2 pressure sensitive area. It responded to an increase in pressure with an increase in capacity. The author used this device to measure the pressure at selected areas under the foot during walking barefoot. The result showed that the second metatarsal head had far more load than the first metatarsal head for normal subjects during the forefoot phase. For anaesthetic feet, the pressure under the fifth metatarsal head increased and reached a peak of more than 80 kPa during the take-off phase. He suggested that this peak was excessive and dangerous for people with anaesthetic feet.

Scranton and Mcmaster (1976) utilized a transducer to quantify local plantar forces using shear sensitive liquid crystals [72]. Interference patterns from a liquid crystal plate mounted in a walkway were filmed from below with a camera. Their results indicated that considerable insight could be gained from the measurement of pressure distribution, but their photographic display was not used for quantitative analysis [14].

Arcan and Brull, in 1976, constructed a device using techniques for assessment of force distribution for standing individuals [3]. Approximately circular of interference rings were generated at discrete locations beneath a transparent platform. The diameter of the rings corresponded non-linearly to local pressure. Cavanagh and Ae [14] used this device to measure the pressure during slow walking in both barefoot and tennis shoe conditions. During walking in tennis shoe, a peak pressure of 1018 kPa was recorded in the heel and a peak pressure of 860 kPa in the forefoot. No large peak was found in toe region during walking in tennis shoe as was found in barefoot walking (600 kPa under the first and second toes).

Nicol and Henning (1976) developed capacitive transducers and multiplexing techniques for the assessment of force distribution with flexible mats [49] [50]. A rubber mat was sandwiched between two matrices of copper strips (16 x 16). The strips of row i and column j formed a condenser Cij. When force was applied, the mat deformed and changed the capacitance measured across the copper grids. Multiplexing techniques were used to assess the forces acting on each condenser Cij. Alternating current was sequentially connected to each row by a de-multiplexer switch whereas the columns were connected to a resistor via a multiplexer switch. This multiplexing circuit required only 32 channels instead of 256 and 32 metal strips instead of 512 single condenser plates. This device was used by Clarke to collect data on 27 subjects at two speeds during barefoot walking [19]. Clarke stated that the peak pressures in the rearfoot, metatarsal heads and toes were higher than those seen in the other regions. The summed peak pressures showed no difference between males and female, and had low correlation with body weight. The midfoot peak pressure was greater for a flat arch than for normal and high arch feet. Generally, peak pressure increased with walking speed. The role of the toes in walking was shown to be contributing to loading for the final 75% of the contact phase.

A piezoelectric device for measuring the vertical contact force generated between the plantar surface of the foot and the insole of a shoe during walking and running was developed by Henning and coworkers in 1981 [31]. 499 piezo ceramic transducers were embedded in a large highly resilient silicon rubber, which was electrically isolating and impermeable to moisture. Each sensor was connected through a cable to a data collection unit. According to their report, the device was capable of following 1 Hz to 1 kHz compressive stress pulse and could reach a peak stress as high as 1500 kPa with an accuracy of a few percent. The linearity was better than 2% and the hysteresis less than 1%. However, this device had problem of a large number of cables and seems not to be used any more.

Maness et al (1987) developed ultra thin conductive type transducers to quantify force distribution in various applications [42]. The sensor used the same multiplexing idea as Nicol. N rows and m columns of conductive material were used in the top and bottom layers which were very thin. The material between the rows and columns functioned as a resistance and consisted of "force sensitive ink". The change in resistance of the material corresponded to the applied force. This measurement system may be used for pressure measurements in human locomotion studies, shoe design, medical clinics and dentist [57] [59].

The current level of sophistication attained in pressure distribution measurement allows accurate and high resolution of instantaneous and cumulative pressure which occurs between foot and shoe, shoe and playing surface. Most of current pressure measuring systems commercial available are based on the capacitive and conductive sensor techniques.

2.2.2 Clinical Applications

Several studies involved the assessment of plantar distribution of forces in normal gait [22] [28] [19] [13] [7] [35] [77] [37]. It was found that in barefoot walking, heel strike is initially on the posterolateral aspect of the heel [37]. The peak pressure at the heel was not reached until approximately 25% of stance phase, and at which point, the heel, lateral midfoot and metatarsal were all making contact with ground

[77]. High velocity of center of pressure in heel strike was found by Cavanagh and Ae and indicated rapid forward transfer of force. As weight transferred from the heel to the forefoot, the center of pressure passed through the midfoot region, but this point represented an average forefoot and hindfoot forces rather than a true peak pressure in the midfoot area [13]. Total heel and midfoot contact time was about 50% of stance. As early as 40% of stance center of pressure was located in the forefoot and its velocity was remarkly decreased. The low velocity of the center of pressure in the forefoot indicated the significant contribution of the metatarsal heads to weight bearing [28]. The peak pressure reached at 80% of stance [77]. In the procession of the stance phase, the center of pressure finally migrated medially across the metatarsal break and terminates in the region of the great and second toe at push off [28] [37]. The metatarsal heads were in contact with the ground about 60%-80% of a walking stance phase and the toe contact time was 50%-55% of stance [77].

Various results were provided about location of highest peak pressure in normal barefoot walking. Soames reported that the highest peak pressure and ground reaction force were under the third metatarsal head [77]. Peak pressure under the first metatarsal head was as two times large as that of the highest pressure of other metatarsal heads [35]. The greatest pressure was six times that of the highest value of lesser toes [35]. A comparison of forefoot to heel indicated that the average pressure of the forefoot was as two to five times as that of the heel [1] [28] [77].

Henning and Rosenbaum used a capacitive pressure distribution platform (EMED) to measure pressure under the foot. They found that the means of the peak pressure values ranged from 59 to 416 kPa with the highest pressure appearing under the hallux (416 kPa) and the third metatarsal head (380 kPa), followed by the first metatarsal head, the medial and lateral heel region and the fifth metatarsal head (321, 321, 284, and 216 kPa, respectively). The lowest peak pressures were found under the midfoot region (59 kPa) [32].

Change of walking speed may change the pressure distribution under the foot. With an increase of walking speed, the weight shifted from the hindfoot to the forefoot and great toe, and the total contact force was increased [1]. Krecklow reported that an increase in the walking speed did not change the medial-lateral displacement of the center of pressure but increased the velocity of the centroid path from the calcaneus to the metatarsal heads [39]. The vertical forces increased under the calcaneus and the metatarsals, but decreased in midfoot with increasing speed. Similar results were also reported by Vaughan [82].

Cavanagh used a 1000 element capacitance transducers to study the plantar pressure in running. He found rapid transferring of weight to the medial heel after lateral heel strike and a concentration of forefoot pressure under the first and second metatarsal heads [12]. In barefoot running, the proximal phalanges contributed minimally to push off. Cavanagh pointed out that plantar pressure distribution was likely much different from running in shoes which distributed weight-bearing more widely and greatly reduced peak pressure compared with running barefoot. Cavanagh and Rodger showed that the mean value of peak pressure were 868 kPa and that the peak value occurred for all subjects in the rearfoot for barefoot running [16]. The average impulse in forefoot was twice as large as in hindfoot. The ratio of the rearfoot/forefoot peak pressure was from 1/1 to 1/5 during running and illustrated the dominance of the forefoot in weight bearing.

Pressure measurements for walking and running remained individually consist, but variable between subjects [7] [19] [34]. There is low correlation between gender as well as body weight and pressure pattern [19] [77] [32].

Pressure distribution can be effectively used to provide insight into the influence of foot structure on response to various applied loads. Cavanagh and Ae used pressure distribution measurement to delineate differences in foot type [13]. The feet of 39 subjects were divided into planus, normal, and cavus groups by clinical examination. Each foot was divided into three anatomical regions: forefoot (40% of foot length), midfoot (30%), and rearfoot (30%). The investigators found significantly higher mean loads in the midfoot for the planus foot group (15% of body weight) versus normal (9%) and cavus (3%).

Clarke found that the peak pressures in lateral midfoot for planus and normal feet were significantly higher than that for cavus feet, and that the peak pressures in medial midfoot for planus feet were significantly higher than for normal and cavus feet [19]. Both planus and cavus feet showed higher impulses than the normal feet in the lateral toe region.

An investigation of dynamic pressure pattern of foot types indicated that the pressure distributions provide much information in mid stance of walking, when the high arch foot showed almost no pressure in the mid portion of the foot [26]. The heel pressure was relatively low for the flat foot. In the midfoot region the flat foot had low level but well-distributed pressure. In the metatarsal region the high arch foot experienced much greater pressure under the first and second metatarsals than the flat foot.

Scranton and McMaster divided foot into five regions: hindfoot, midfoot, metatarsals, great toe and lateral toes to study the force distribution of three foot types. Their results indicated a significant decrease in midfoot contact time and increase metatarsal contact time for a high arch subjects. The force was increased in midfoot and metatarsals and slightly decreased at the great toe for a plat foot subject. [72]

Measurement of plantar pressure distribution was frequently used in the studies of diabetic foot [9] [21] [67] [79] [84]. The results of these studies showed that the diabetic foot had abnormally high pressure under the forefoot and midfoot. A decrease in toe loading was also found with increasing neuropathic involvement.

Pressure distribution was also used in study of shoe type. Raley measured the plantar pressure with five kinds of footwear (bare foot, preferred, flexible, ripple and rockered sole shoes) during walking [58]. He found that the duration of pressure in the second metatarsal-phalangeal joint was significantly less for the barefoot condition than for the preferred shoe, flexible shoe, and rockered sole shoe conditions, while the difference was not significant for the ripple sole shoe condition. The pressure-time-integral was found to be less for the rockered sole shoe and the ripple sole shoe than for the remaining shoe conditions, while this variable was less for the rocked sole shoe than for the ripple sole shoe. For both the preferred and flexible shoe conditions, the recorded maximum pressures were greater than those for the rockered sole and the ripple sole shoes. No significant differences between the shoe conditions were found for time to maximum recorded pressures.

Hamilton et al compared the pressure distribution between comfortable and non-comfortable shoes [29]. The foot was divided into nine sections: lateral and medial heel; lateral and medial midfoot; lateral, medial and interior metatarsal heads; hallux and the proximal phalanges. Significant differences were found in the midfoot and heel. The results showed that less comfortable shoes consistently took more load on midfoot. The load on the medial aspect of the midfoot reached a peak earlier in the step cycle than for less comfortable shoes. Peak pressure on the heel was larger for less comfortable shoes. According to the result, the authors suggested that the pressure measurements may be applicable for the assessment and quantification of comfort.

CHAPTER 3

EVALUATION OF THE FSCAN AND EMED PRESSURE MEASURING SYSTEMS

3.1 INTRODUCTION

Fscan (Tekscan Inc., Boston) and EMED (Novel Gmb., Munich) force sensing insoles are available for the measurement of pressure distribution between the plantar surface of the foot and the shoe. The quality of these measurements is directly influenced by the accuracy of these systems, especially when quantifying result of the measurement is needed. The purposes of this study are (1) to assess selected characteristics related to the accuracy of Fscan and EMED pressure measurement systems (2) to compare these two systems and (3) to discuss the possibilities of Fscan and EMED for studies related the comfort of shoes.

The Fscan System

The Fscan force distribution sensor insole is based on resistive sensors which rely on a conductive flexible substrate [57]. Multiplexing techniques [49] [50] are used for the construction of the insole. The insole consists of two layers of flexible elastomers with a grid of rows and columns. The rows are on one layer and the column on the other. The rows and columns are made of an ink that contains conductive material suspended in a polymer binder. When a force is applied to a crossing of a row and a column, the contact area between the traces increases as a result of deformation of the elastomers, thereby reducing the resistance between the row and column (Fig.

3.1). This resistance is determined by applying a voltage to each row and measuring the current output at each column. The applied force is a function of the determined resistance [42]. The tested Fscan insole had 60 rows and 21 columns which formed 1260 individual force sensing points. The pressure can be calculated with the area of each sensor. The circuit for obtaining and transmitting data from the insole is connected with each column. Figure 3.2 gives a simplified schematic diagram of the Fscan system. The model of the Fscan insole used in this study is FF (032291). The insole can easily be trimmed into a required foot size. The sampling frequency is 50 Hz.

The EMED System

The EMED force measuring insole is based on the capacitance principle, using the phenomenon that the capacitance of a capacitor changes when the distance between the two plates changes. Similar with Fscan system, the EMED insole uses the multiplexing techniques developed by Nicol [49]. Dependent on the material between the plates, the dielectricum, an applied force will change the interplate distance and therewith the measured capacitance (Fig. 3.3) [56]. With proper calibration, the relation between measured capacitance and applied force can be found. Flexible foils are used for the construction of the EMED insole. If not specified, the EMED insole used in this section was model z378, which had 85 capacitance sensors and was of size 9. The sampling frequency is 100 Hz. For EMED insole, there were no sensors in two small areas, where the wires connected to the sensors pass by. One area is located between midfoot and heel, and the other was in the lateral midfoot.

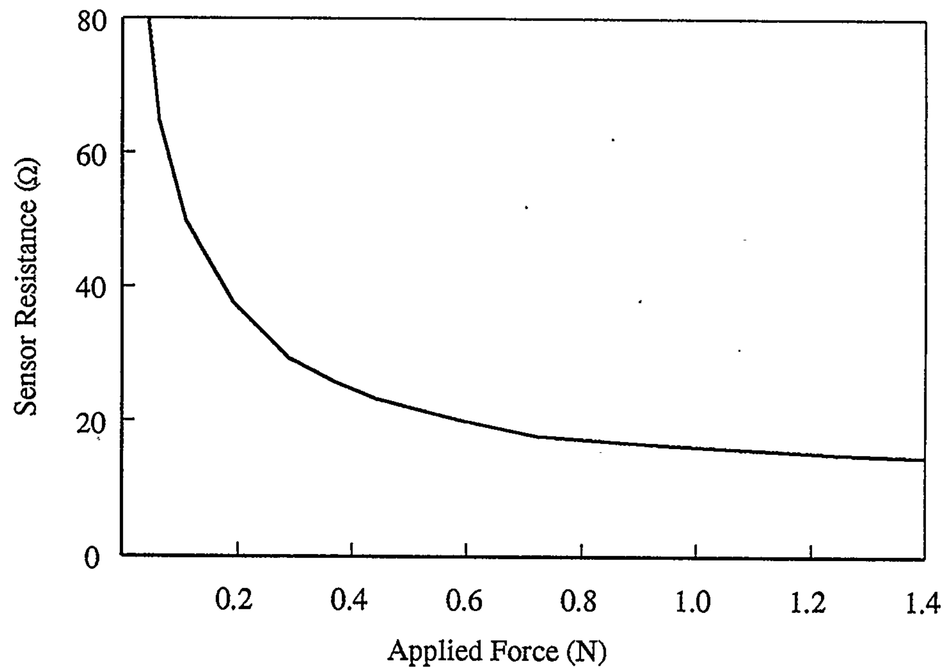
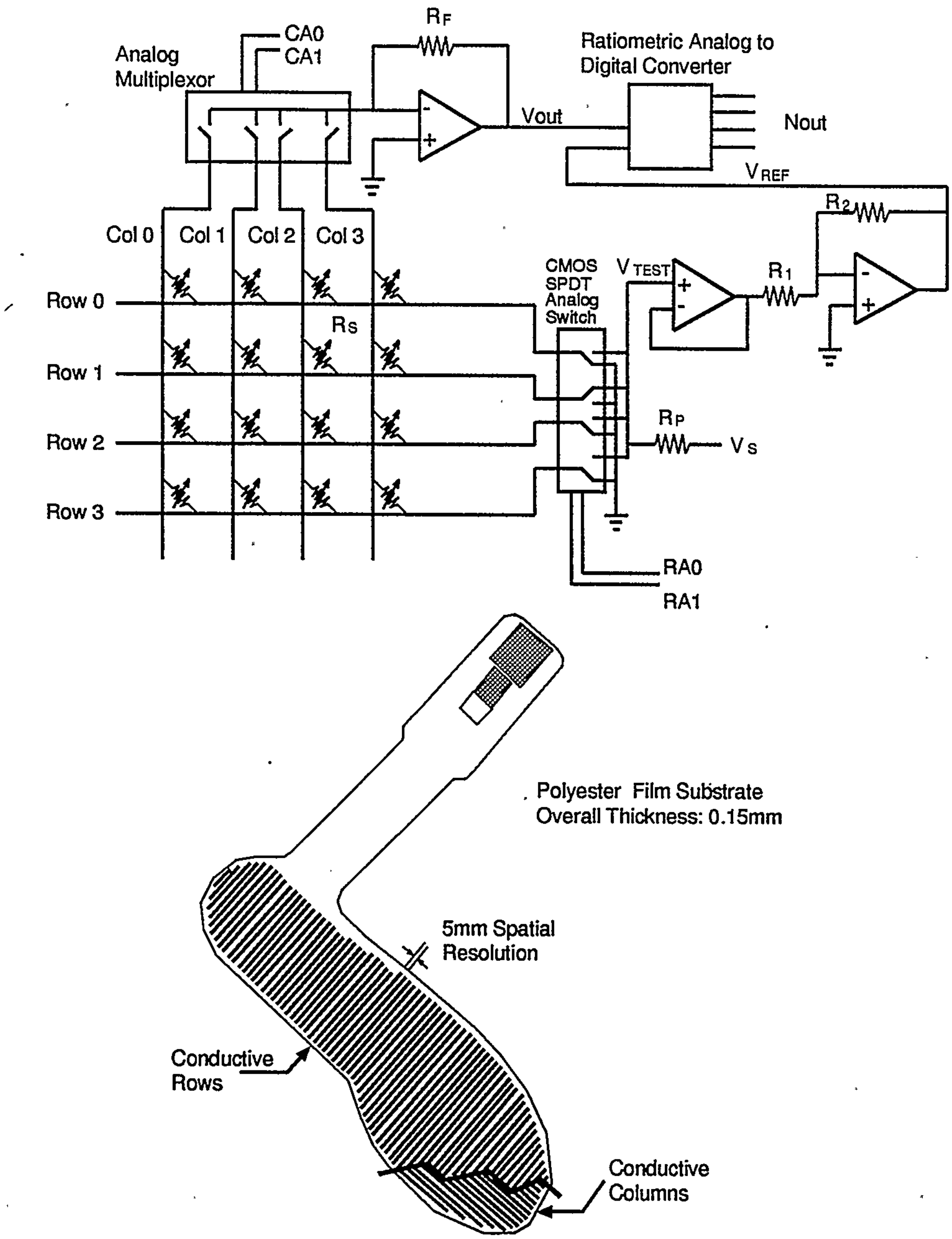


Figure 3.1. Illustration of resistance response with change of applied force.



This simplifiled circuit can scan a four row by four column sensing area.Each potential circuit location is respresented as a variable resistor whose value is virtually infinite when no force is being applied. The sensor is read sequentially by driving one of the row electrodes and sensing one of the column electrods. For this illustration, the circuit is shown reading the resistor at the intersection of row1 and row2 (From: *Podolloff and Benjamin, Sensors, 3, 41-47, 1989).*

Figure 3.2. Simplified schematic diagram of Fscan system.

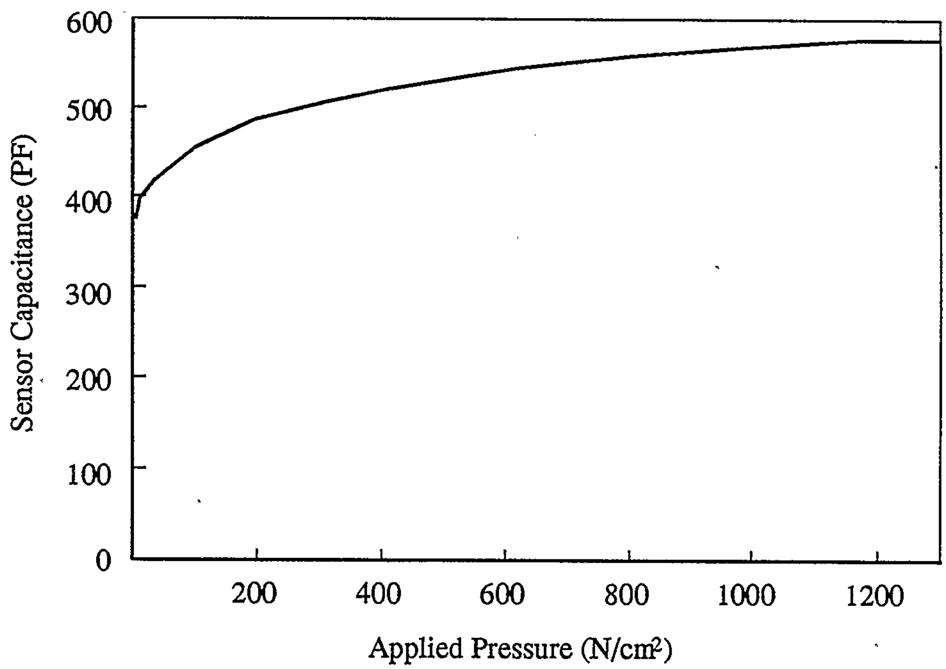


Figure 3.3. Illustration of Capacitance response with change of pressure.

3.2 TESTING OF THE CHARACTERISTICS

Several important characteristics influencing force distribution measurements such as linearity, hysteresis, threshold of the system, temperature response, and crosstalk were investigated in this study. A calibration device based on air pressure (see Fig. 3.4) was used to apply a known equally distributed force on the insoles. The applied and measured pressure were used as variables for comparison.

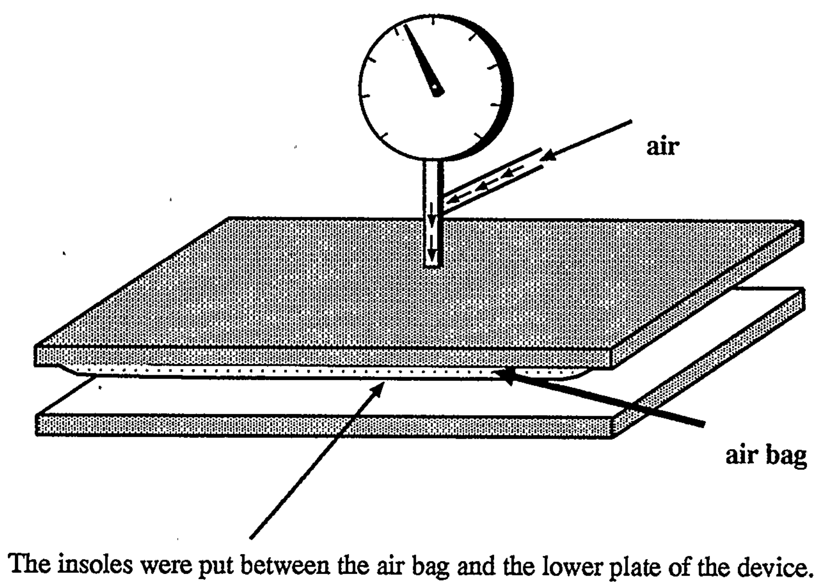


Figure 3.4. Simplified schematic diagram of air pressure device for the pressure calibration.

3.2.1 Linearity and hysteresis

Method

To test the hysteresis of the system, gradually increasing pressure was applied on an untrimmed and not used insole. The insole was loaded from 0 kPa to 500 kPa and unloaded from 500 kPa to 0 kPa with steps of 50 kPa. For testing the linearity two methods were involved: (1) appling pressure in the same way as loading procedure in the hysteresis test, (2) appling pressure every time from 0 kPa to the specific pressure

(50, 100, 150 ..., 500 kPa).

Results

The results shown in Fig. 3.5 and Fig. 3.6 indicated a close linear relation between the applied pressure and measured pressure for Fscan and EMED systems. It can be described in a mathematical with

$$P_{out} = kP_a \tag{3.1}$$

where P_{out} is the measured pressure, P_a is the applied pressure and k is a constant.

The value of k was for Fscan 0.67 and for EMED 1.02. This corresponds to a underestimation of the registered pressure with the Fscan system and a close estimation of the pressure with the EMED system. The good results of the EMED system are due to the possibility to calibrate each sensor of the system individually, while the possibility is not present in the Fscan system.

The results for the hysteresis test are also shown in Fig. 3.5 and Fig. 3.6. A hysteresis of 18% was found during a loading-unloading process for the Fscan insole. The highest hysteresis for the EMED insole was 8%. These data is not in agreement with the hysteresis of 3% reported by the manufacturer for both systems.

3.2.2 Threshold

Method

To measure the threshold of both systems, a stepwise (10 kPa) increasing pressure was applied on the insoles from 0 kPa to a pressure at which the measured pressure was in agreement with the linear curves shown in Fig. 3.5 and Fig. 3.6.

Results

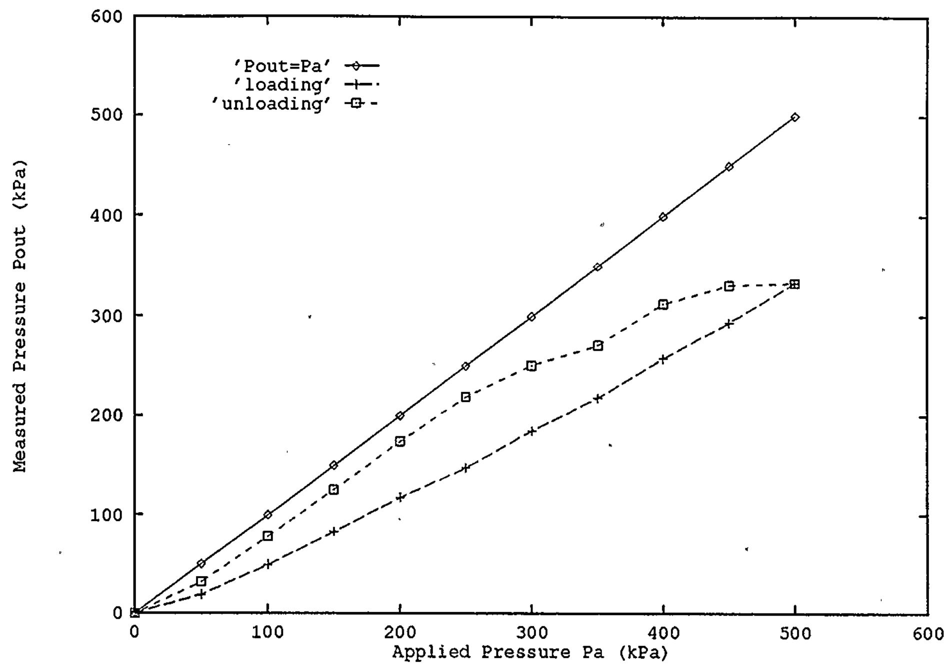


Figure 3.5. Applied pressure versus the with Fscan measured pressure.

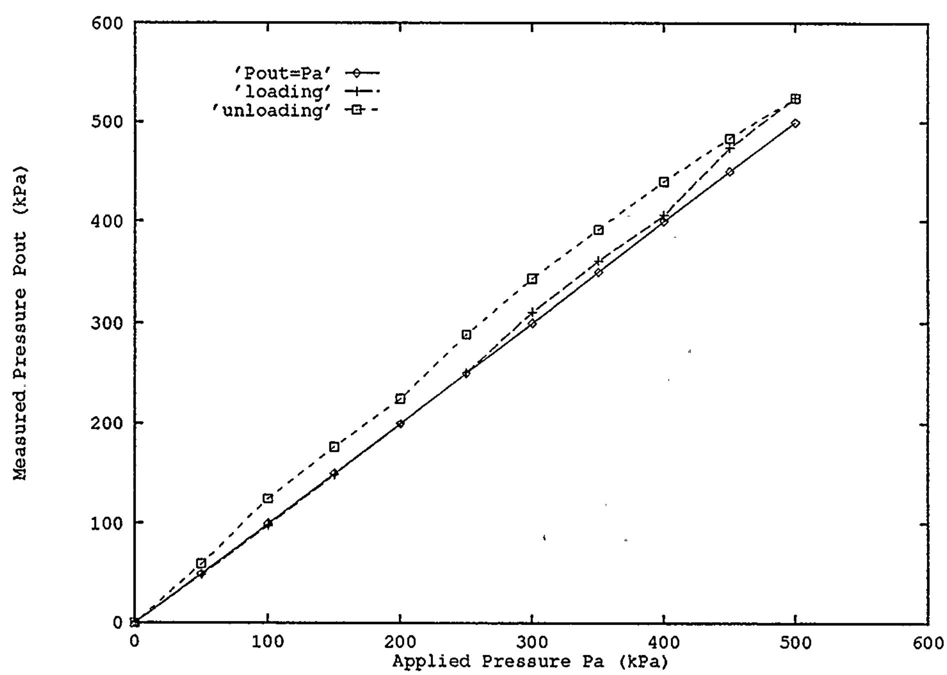


Figure 3.6. Applied pressure versus the with EMED measured pressure.

The results for the test were displayed on Fig. 3.7 and Fig. 3.8. The results show that the lowest sensitive pressure was 40 kPa for Fscan and less than 10 kPa for EMED respectively. The pressure on which the measured pressure was in agreement with the P_{out} - P_a curve of Fig. 3.5 and Fig. 3.6, was 100 kPa and 50 kPa for the Fscan and EMED respectively. The EMED system overestimated the pressure below 50 kPa; the Fscan system underestimated it. The result indicated that the EMED system had higher sensitivity in the low pressure region than the Fscan system.

3.2.3 Temperature

Methods

The test to measure the influence of temperature on the measured pressure was divided into two parts. In the first part, the pressure was recored at four different temperature conditions: freezing point (0^0C), room temperature (23^0C), body temperature (37^0C) and 60^0C. In the second part, the pressure was measured after the temperature of the insole was returned naturally from the special temperature to the room temperature. For all the recordings, the applied pressure was 250 kPa. To prevent the insole for damage, the EMED insole was only tested at room and body temperature.

Results

The results for the temperature test are summarized in table 3.1. The results of the Fscan system indicate that the measured pressure was not influenced by the temperature between freezing point and body temperature (This temperature range was defined as normal temperature). However, when the temperature was 60^0C, the measured pressure increased significantly and even after the temperature of the insole was returned to room temperature, the previously heated area still recored a higher

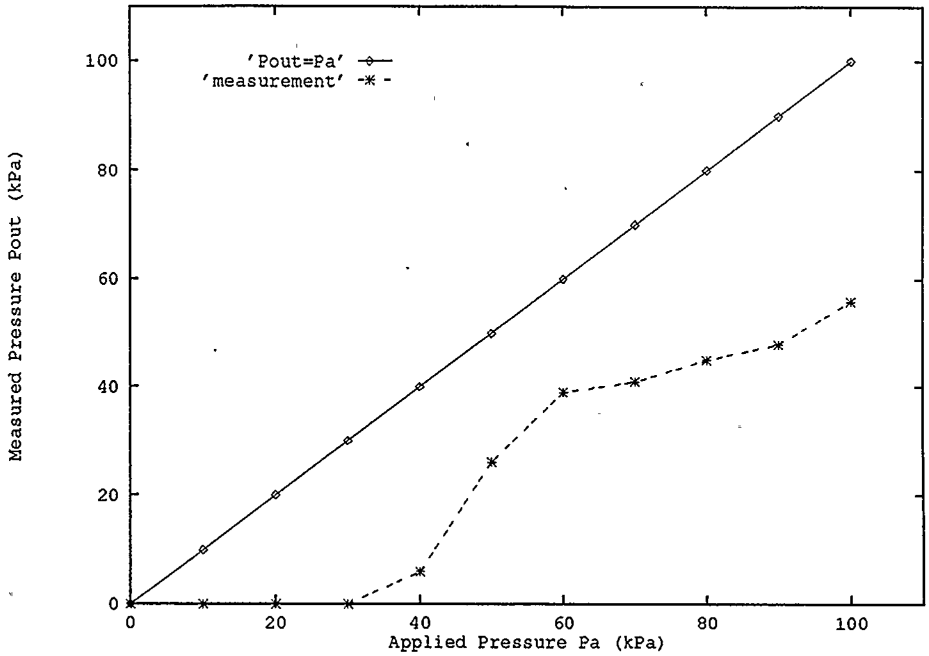


Figure 3.7. Measured pressure in the low applied pressure region for Fscan system.

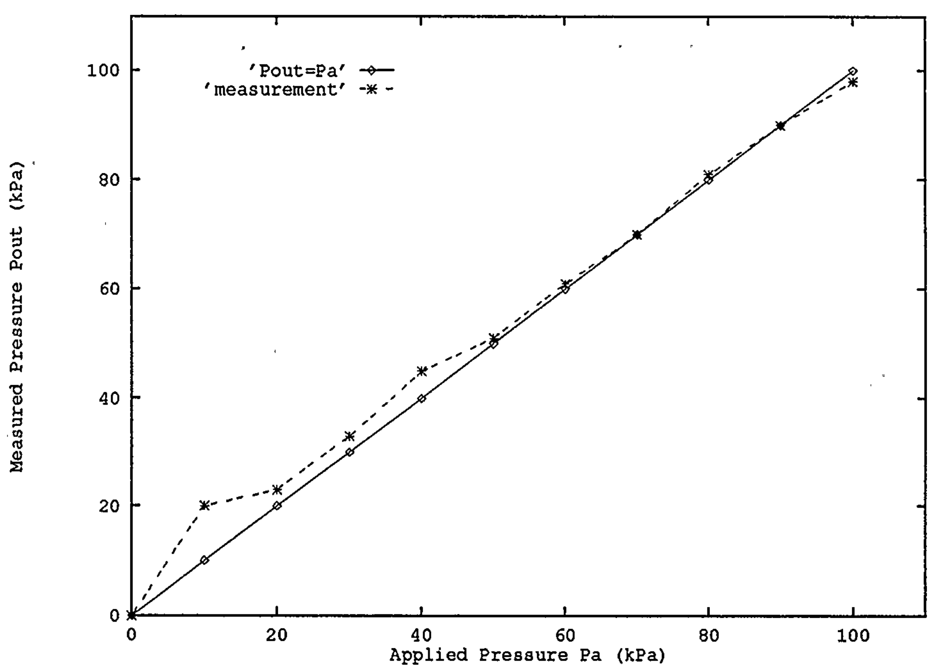


Figure 3.8. Measured pressure in the low applied pressure region for EMED system.

Illustrition of Results of Measured Pressure (Applied Pressure = 250 kPa)

System	Temperature	0 °C	23 °C	37 °C	60 °C
Fscan	part 1 (kPa)	153	153	149	358
	part2 (kPa) (23 °C)	149	151	148	222
EMED	part 1 (kPa)		251	249	
	part2 (kPa) (23 °C)		253	251	

Table 3.1. The effect of temperature on the measured pressure for the Fscan and EMED systems.

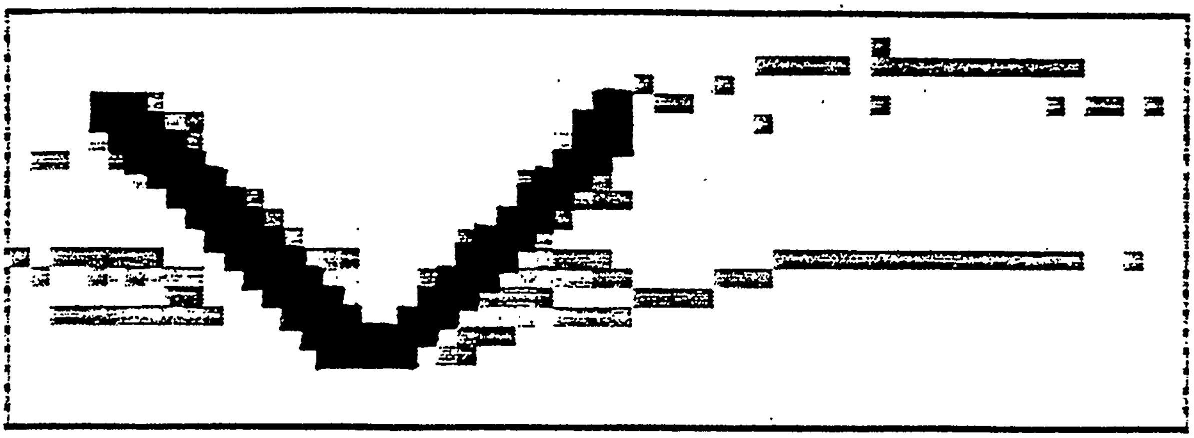
pressure than in the normal situation. It may be that the sensors were destroyed due to the high temperature.

For the EMED system, no difference in measured pressure was found between room temperature and body temperature.

These results suggested that there were no temperature effects on the measured pressure under body temperature.

3.2.4 Crosstalk

The Fscan system is designed in a way that the resistance between the rows and columns can be scanned continuously. This is done by appling a certain voltage on a row and measuring the current on a column. Force acting on the particular crossing of a row and a column determines the resistance and therewith the measured current. In this design, it can be possible that a force in the neighborhood of a scanned row and column crossing produces a current flow from the row on which the voltage is applied to the scanned column. If this is the case, the measured signal is not a result of a force acting on the intersection of a row and column, but from forces in the surrounding of the scanned sensor. This phenomenon is called crosstalk and can be defined as a signal at the output of a transducer caused by a variable acting on this transducer but not allocated to this particular output. To test this phenomenon, applied force was simulated by using a liquid conductor (ECG electrode conductor) between the two layers of the insole at selected row and column crossing. The liquid conductor can decrease the resistance between the row and column and simulate a (high) force. In an ideal situation, the output of the simulated pressure should only be showed in the selected sensing points where the conductor was applied to. However, the results of the crosstalk test demonstrate that many sensing points provided an output of measured pressure (see Fig. 3.9). These results suggest that crosstalk could be a problem with the Fscan system.



The simulated pressure was applied at the points which are shown in the dark V area

Figure 3.9. Crosstalk test for Fscan system.

A similar method was not possible with the EMED insole. But when pressures were applied on individual sensors of the EMED insole, the output was shown exactly on the area where the pressure was applied. These results indicate that crosstalk seems to be not critical for the EMED system.

3.2.5 Additional tests

It seems that the accuracy of the Fscan system is not only depended on the loading rate but also is influenced by the loading sequence, the number of times the insoles is used, and the loading state (dynamic, static). A number of additional tests were done in this section.

3.2.5.1 Influence of loading sequence

Method

Pressure was applied on the Fscan insole in two different loading sequences. In one experiment the pressure (250 kPa) was applied to the insole directly from 0 kPa to 250 kPa. The pressure was released to 0 kPa after recording. In another experiment the pressure (250 kPa) was applied to the insole by decreasing the pressure from 400 kPa to 250 kPa. Ten trials were taken in each of experiments.

Result

The difference in measured pressure between the two loading methods is significant (Fig. 3.10). The difference (22%) could be caused by hysteresis because the result of the "0-250-0 sequence" and "400-250-400 sequence" were in agreement with the loading-unloading curves shown in Fig. 3.5. This means that the pressure patterns measured during walking or running strides can be effected by the loading and unloading sequence.

3.2.5.2 Influence of number of times the insole was used

Previous pressure measurements with Fscan sensor insole showed a reduction of the sensitivity of the insole after a number of trials. For testing the influence of the number of steps on the sensitivity of the insole, calibration measurements were done before and after use of the insole at a applied pressure of 250 kPa. Calibration measurements were done after 100, 200, 300 and 400 steps. The result is shown on Fig. 3.11.

A trend of reduction in measured pressure was clearly shown from 0 to 400 steps. The largest reduction was found after walking 100 steps (17% in forefoot, 11% in midfoot and 16% in rearfoot). A smaller reduction of measured pressure was shown after walking 200 steps comparing to that of 100 steps. The reduction rate was 5%-7% when walking from 200 to 400 steps for the whole sole (forefoot+midfoot+rearfoot).The experiments also indicated that the reduction of sensitivity was related to the loading rate of the insoles. The midfoot loading by walking is less than the loading of forefoot and rearfoot. Fig. 3.11 shows that after 300 steps, the measured pressure in midfoot area was still 5% higher than that in forefoot and rearfoot areas.

Results of a hysteresis test after 400 steps (Fig. 3.12) shows the same patterns as described before (Fig. 3.5).

Same measurements described above were also done with the EMED system. The results indicated no significant influences of the above factors on the pressure measurement for the EMED system.

Another result of these measurements is about the influence of trimming the Fscan insole. When the Fscan insole was trimmed, the output pressure was overestimated (Fig. 3.13) and the gain value was close to 1. However, after walking several hundred steps, the gain was returned to 0.6-0.7, which was near to the level of the untrimmed insole. This result suggest that the sensitivity of the Fscan system was changed by trimming the insole.

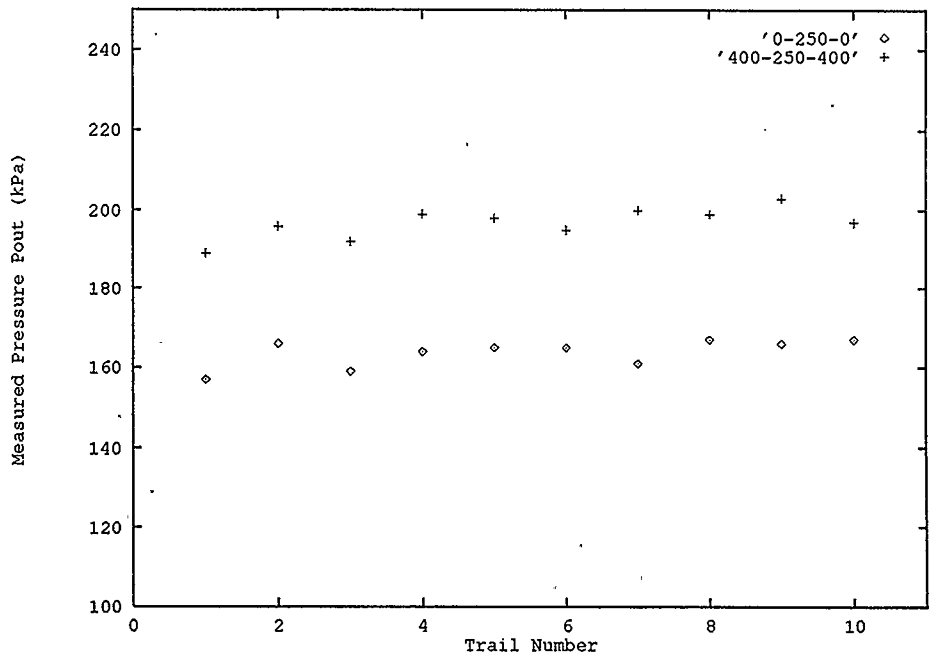


Figure 3.10. Influence of loading sequence on the measured force for Fscan system.

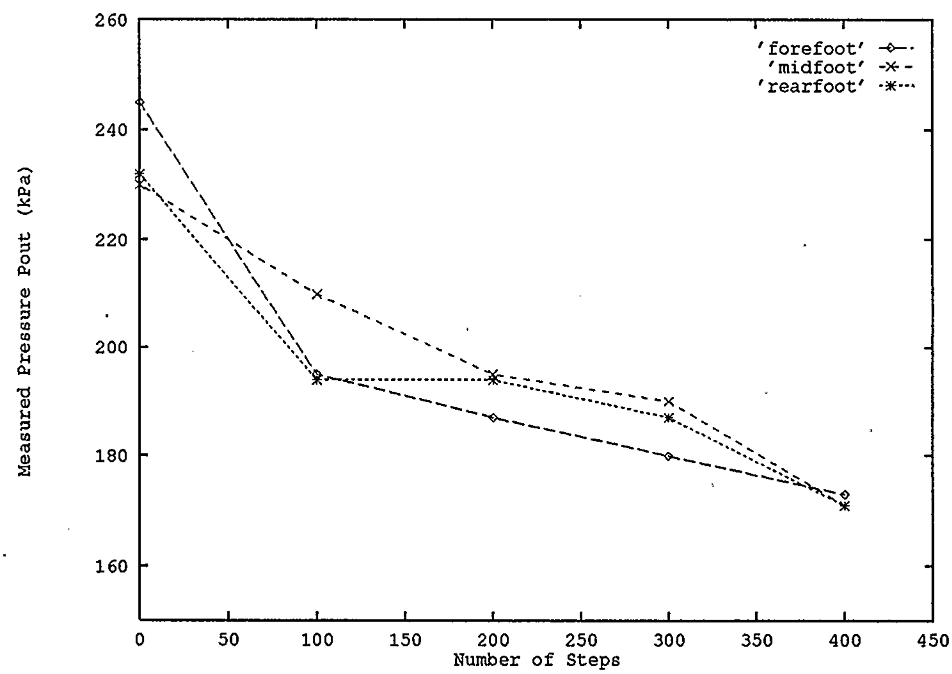


Figure 3.11. Influence of number of steps on the measured force for Fscan system.

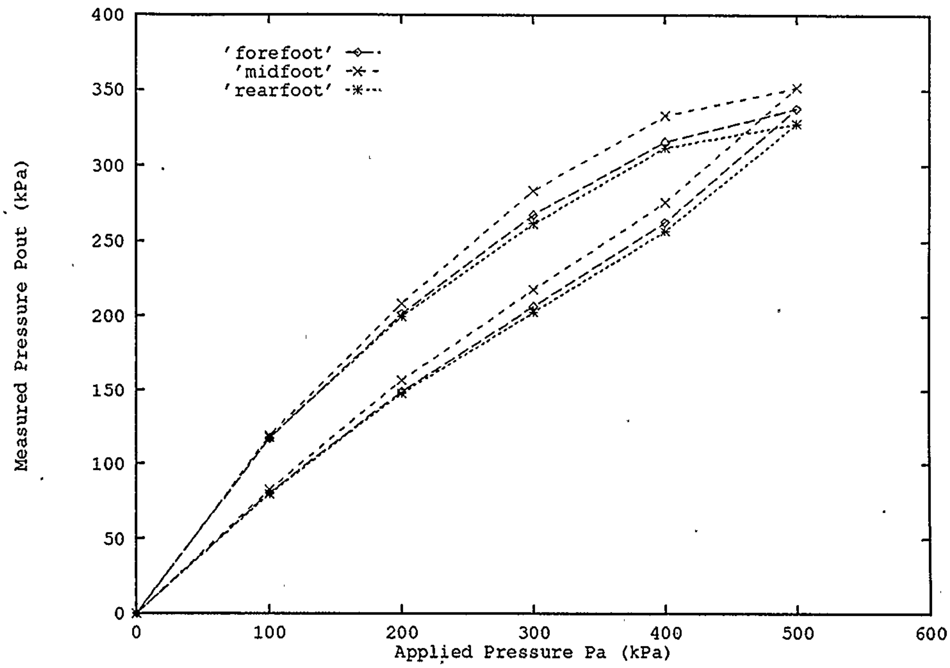


Figure 3.12. Loading-unloading curve for a used Fscan insole.

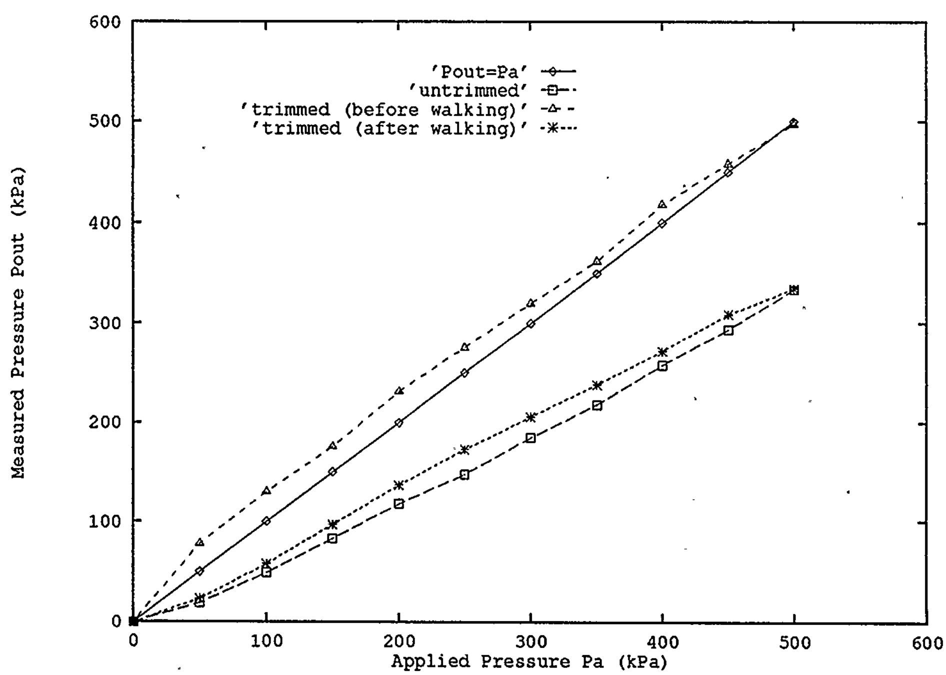


Figure 3.13. The effect of cutting the Fscan insole to the right shoe size.

3.3 DYNAMIC RESPONSE OF EMED and FSCAN SYSTEMS

In order to estimate the accuracy of the measurements by using Fscan and EMED systems, the ground reaction force (GRF) by walking and running was measured with three systems: Kistler platform, EMED insole system and Fscan system. Kistler force platform is a high sensitive force measuring system and has good resolution for the measurement of ground reaction force. The sampling frequency of the Kistler force platform is 1000 Hz. In this section, the ground reaction force measured with EMED and Fscan system was compared to the ground reaction force measured with Kistler force platform.

Method

To measure the ground reaction force simultaneously, a EMED and a Fscan insole were put overlapped and taped to the surface of the force platform. A subject was introduced to locate his left foot (barefoot) just on the insoles tapped to the force platform when he walked and ran through the force platform. The ground reaction force was recorded with the three systems in the meantime. Five trials for each movement were recorded.

Results and discusions

The results for the measurement are shown on Fig. 3.14 and Fig. 3.15. For walking movement, the GRF-time curve of EMED was in a good agreement with the curve of force platform except 14% difference in the first peak of the force. This difference may be caused by the no sensor area between the midfoot and heel of the EMED insole. The result measured from Fscan system underestimated the force up to 27%. For running movement, the measured GRF was underestimated up to 22%

for EMED system and 33% for Fscan system during the most of gait circle, separately. However, the GRF was overestimated during the taking off phase for both Fscan and EMED systems. The results for EMED system were constant for each trial of the measurements. So the error for EMED system can be considered as systematic error.

For heel-toe running, the ground reaction force had two peaks. The first peak is called impact force which is the force due to a collision of foot and the force plateform. The second peak is active force which is the force due to movement controlled by muscular activity. In order to measure the impact force, high sampling frequency is required. Due to the low sampling frequency, the present Fscan and EMED systems could not measure the impact force accurately (Fig. 3.15). However, the sampling frequencies of the two systems were high enough to measure the active force. If not consider the impact force, the sampling freqency of the Fscan and EMED systems would not be the main cause of measurement error.

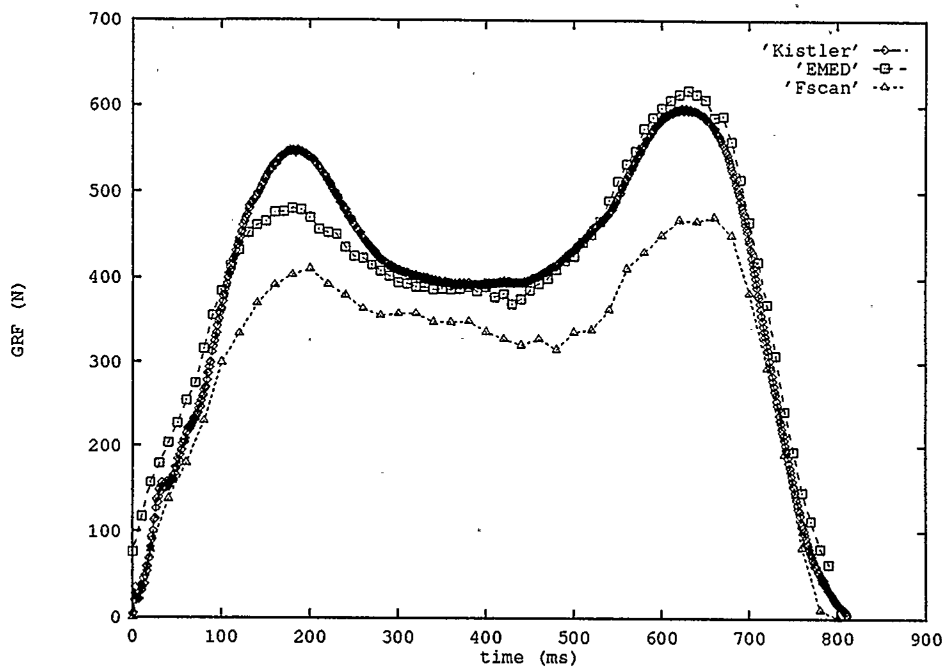


Figure 3.14. Ground reaction force for walking.

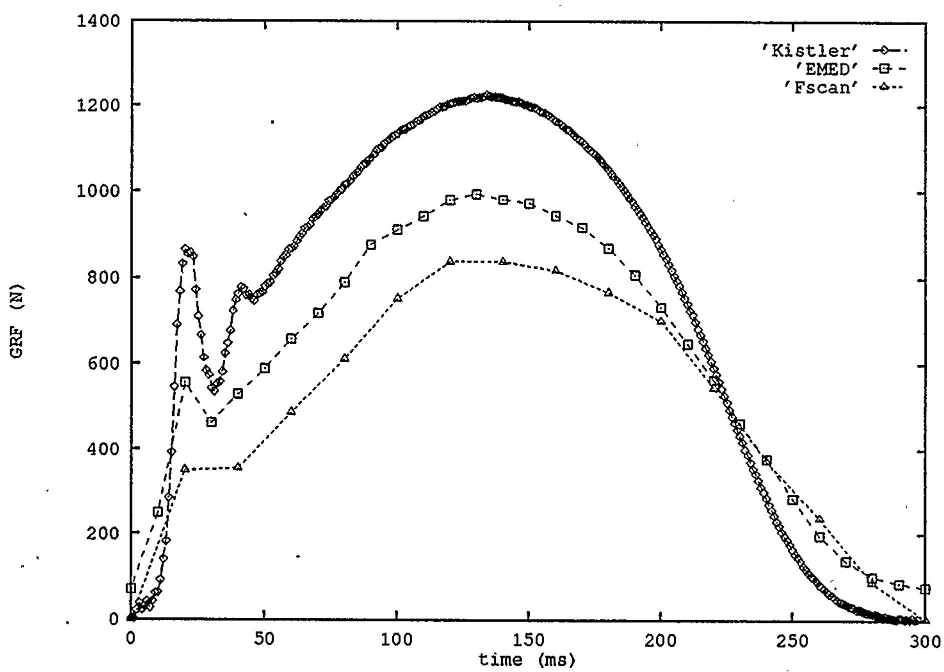


Figure 3.15. Ground reaction force for running.

3.4 SUMMARY

3.4.1 Summary of testing results

1. The relation between the measured pressure and the applied pressure is linear. The gain between the applied pressure and the measured pressure is approximately 0.6-0.7 for Fscan and 1.0 for EMED.

2. The hysteresis is 18% for Fscan and 8% for EMED. This is a considerable accuracy influencing factor.

3. The threshold is 100 kPa for Fscan and 50 kPa for EMED.

4. The temperature effects did not influence the measurements in a temperature range between 0^0C and 37^0C.

5. Crosstalk was shown in the Fscan system. There was no evidence of crosstalk in EMED system.

6. The loading sequence, the insole trimming and the times the insole was used can influence the accuracy of the measurements with the Fscan system.

7. The ground reaction force was underestimated by using Fscan system for both walking and running movement.

3.4.2 Comparison of the Fscan and EMED systems

Advantages and disadvantages:

1. The accuracy of the EMED system is better than the accuracy of the Fscan system. An advantage of the EMED is the possibility for calibration.

2. The Fscan insole can be trimmed to fit any size. The size of the EMED insole is fixed.

3. The Fscan data collection procedure is simple. The data can directly be transferred to the computer and showed on line on the screen dynamically during the data collection. The operation of the EMED system is relatively complicated.

4. The sampling frequency for Fscan is 50 Hz. This seems to be low for fast movement such as running. The frequency of the EMED system can be set from 1 to 100 Hz.

5. The Fscan insole is very thin comparing to the EMED insole. This reduced the influence of the insole thickness on the measurement. However, the Fscan insole is less flexible than the EMED insole and is easily damaged. The EMED insole has good flexibility and can be used much longer than the Fscan insole.

6. The EMED system has a full package of software for data analysis. The software of the Fscan system for data analysis is relatively limited.

7. The largest disadvantage of the EMED insole is its high cost. One insole costs more than one thousand dollars, whereas, the Fscan insole only costs a few dollars.

3.4.3 General conclusion

In the present condition, the Fscan insole force distribution system can only be used for qualitative measurements of the pressure distribution during walking or running (e.g. in clinical research). The EMED system seems to satisfy the accuracy requirements for scientific studies and can be used for quantitative measurements. However, the systematic error should be considered when the force measurement is conducted by using EMED system for the running movement.

CHAPTER 4

RELATION BETWEEN PRESSURE DISTRIBUTION UNDER THE FOOT AND INSOLE COMFORT

4.1 INTRODUCTION

Shoe comfort is one of the most important aspects for shoe manufactures and shoe markets. However, the definition and quantification of comfort is still an unsolved problem. Comfort has been described as a subjective feeling depending on individual differences and it has been suggested that it cannot be measured directly [11] [74]. Additionally, subjective assessments of comfort are difficult to interpret. What is "comfortable" to a group of people may be "uncomfortable" to others, based on their personal preferences and what they have become accustomed to [73] [83].

Limited research is available concerning a possible scale in which comfort can be measured. Is it a continuous or a discontinuous scale, and if continuous, is it linear or logarithmic? However, there may be a relationship between perceived comfort and certain measurable parameters such as force, pressure and energy cost. Krouskop used the pressure measurement in an above-knee socket to provided an information of comfortable socket [40]. In Nowroozi and Salvanelli's study, the energy cost was recorded at several walking speeds and a comfortable walking speed was demonstrated when the energy cost was lowest [55]. Impact testing results described by Whittle and coworkers was used to relate the cushioning properties of carpets to perceived comfort in walking [83].

Pressure distribution inside the shoe is of great importance for orthopaedic and biomechanical considerations. In sports, safety and comfort may depend on plantar pressure distribution, which also may determine whether or not a shoe is well suited for a certain activity [71]. It has been suggested that for comfort, the shoe sole should produce minimal pressure or force between the foot and the insole [11]. If a shoe design does not produce local irritations to the foot and maintains pressure between the plantar surface of the foot and the shoe below a certain threshold value, then the shoe can be perceived as comfortable [25].

Hamilton and coworkers [29] compared the pressure distribution between comfortable and less comfortable shoes during walking in a pilot study on shoe comfort. Subjects were tested in both a comfortable and a less comfortable pair of shoes of their own choice. Significant differences were found in the midfoot and heel. The results showed that less comfortable shoes consistently took more load on both the lateral and medial midfoot. Additionally, peak pressure on the heel was significantly larger, and maximal contact areas of total foot and midfoot were smaller for less comfortable than for comfortable shoes.

The purpose of this study is (1) to determine if pressure distribution at the plantar surface of the foot can be related to the subjective rating of comfort for four different types of shoe insoles, and (2) to investigate the relation between plantar pressure distribution and running shoe comfort.

4.2 METHODS

Fourteen male *subjects* were consented to participate in this study. All subjects were physically active and had size 9 feet. The subjects ranged in age from 23 to 41 years old (mean=28.9, SD=4.5), in height from 170 to 183 cm (mean=177.7 cm, SD=3.4 cm), and in mass from 62.5 to 72.0 kg (mean=66.2 kg, SD=2.8 kg). Before the experiment, each subject was asked to report possible lower extremity injury histories. Four subjects had previous ankle injury and one had a knee injury. However, all these subjects were completely recovered from the injuries by the time of the experiments.

Identically constructed running *shoes* and four pairs of *insoles* designed by Adidas were used in this study. The insoles were designed and made significantly different in shape, hardness, thickness, and flexibility to provide difference in the comfort at the plantar surface of the foot. The four different insoles were used by all subjects in the testing procedures and were referred to as 'EL1', 'EL2', 'EL3' and 'ELts' according to the names used by Adidas.

Normal walking and heel-toe running were selected for the *test movements*. In order to minimize the influence of the speed of walking and running on the pressure measurements [1] [39] [82], both running and walking were performed on a treadmill and the speeds of walking and running were identical for every individual subject in all the insole conditions.

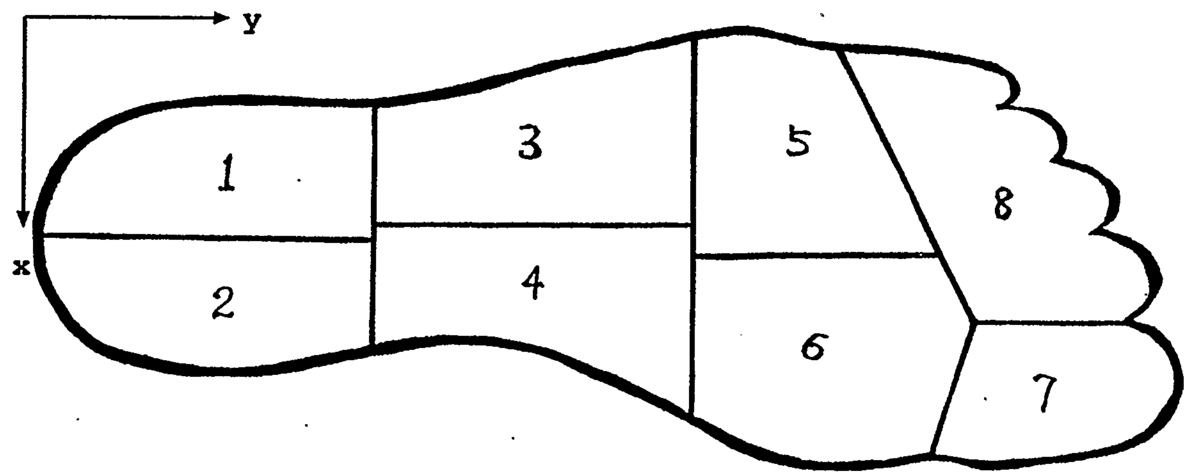
For *data collection*, each subject was instructed to wear each of insoles and to perform walking and running separately at his preferred speed in the first part of the experiment. The trials were stopped when the subjects confirmed to have a certain comfort rating for the insoles. The speed ranged from 5.8 to 7.0 km/h (mean=6.41, SD=0.53) for walking and from 11.5 to 14.0 km/h (mean=12.9, SD=1.14) for running. The speed for each subject was same for all the walking trials and the running trials. The order in which the insoles were tested was randomly selected. After the tests of the four insoles, the subject was asked to rank the insoles in the order of comfort for both walking and running. Rank 1 represented the most comfortable, rank 2, the second comfortable, rank 3, the third comfortable, and rank 4, the least comfortable.

In the second part of the experiment, the EMED insole pressure measuring system was used to measure the pressure and force between the plantar surface of the foot and the shoe. During the data collection, the EMED sensor insole was put between the test insole and the plantar surface of the left foot. Each subject was asked to repeat the same procedures described in the first part of the experiment. Three trials for walking and five trials for running were collected for each subject and each insole condition. To account for a possible change in the feeling of comfort by inserting EMED sensor insole, the four test insoles were ranked again in the order of comfort after the data collection. The most and least comfortable insoles from this new assessment were used for the comparison of the pressure distribution between the plantar surface of the foot and the insoles.

For *data analysis*, the foot was divided into eight sections for the analysis: lateral and medial heel; lateral and medial midfoot; lateral and medial forefoot; hallux and proximal phalanges. Theses regions were created to fit each subject (Fig. 4.1).

Pressure measurements from these regions were analyzed in the form of following variables:

F_{max}	=	maximal force
P_{peak}	=	peak pressure
P_{int}	=	pressure-time integral
F_{int}	=	force-time integral
A_{max}	=	maximal area
x	=	transversal coordinate of center of force path
y	=	longitudinal coordinate of center of force path



1. lateral rearfoot 2. medial rearfoot 3. lateral midfoot 4. medial midfoot
5. lateral forefoot 6.medial forefoot 7. hallux 8. proximal phalanges

Figure 4.1. Division of the foot

The coordinate system was constructed for each foot in which the x coordinate starts from the lateral side of the foot to the medial side of the foot, and the y coordinate from heel to toe (see Fig. 4.1).

All the above variables were used to analyze the data for walking. Because of large systematic error (15-22%) in force measurements for running by using the EMED insole system, only P_{peak}, P_{int} and A_{max} were used in the data analysis for running. The mean values of these variables for fourteen subjects and their standard errors were calculated for the analysis. Statistical analysis was performed with the t-test. The paired t-test was used to compare the comfortable and uncomfortable insoles. Significance was defined when $P < 0.05$.

4.3 RESULTS

4.3.1 Subjective Ranking of Comfort

The results of the subjective ranking of the comfort for the test insoles are summarized in Fig. 4.2.

The results demonstrated that the comfort feeling of the insoles could be very different for different individuals. Insoles which were comfortable for some subjects could be uncomfortable for other subjects. The feeling of comfort also depended on the movement which the subjects performed.

The average ranking of each insole is given in Table 4.1. For running compared to walking, the average ranking was increased by 4% for insole EL1, 22% for ELts and decreased by 12% for insole EL2, 4% for insole EL3, respectively.

Condition	Average Rank							
	Walking				Running			
	EL1	EL2	EL3	ELts	EL1	EL2	EL3	ELts
without EMED insole	1.86	3.00	3.50	1.64	1.93	2.64	3.42	2.0
with EMED insole	2.0	2.79	3.36	1.86	2.0	2.64	3.36	2.0

Table 4.1. Illustration of the average comfort ranking for the test insoles

The results also indicated that the comfort level could change by adding the EMED insole. For walking, the average ranking was 8% higher for insole EL1, 7% lower for EL2, 4% lower for EL3 and 13% higher for ELts after inserting the EMED insole. However, there was little change of comfort ranking by inserting the EMED insole for running.

Analysis of the comfort rating of the test insoles provided the following observations, which were statistically significant for both running and walking:

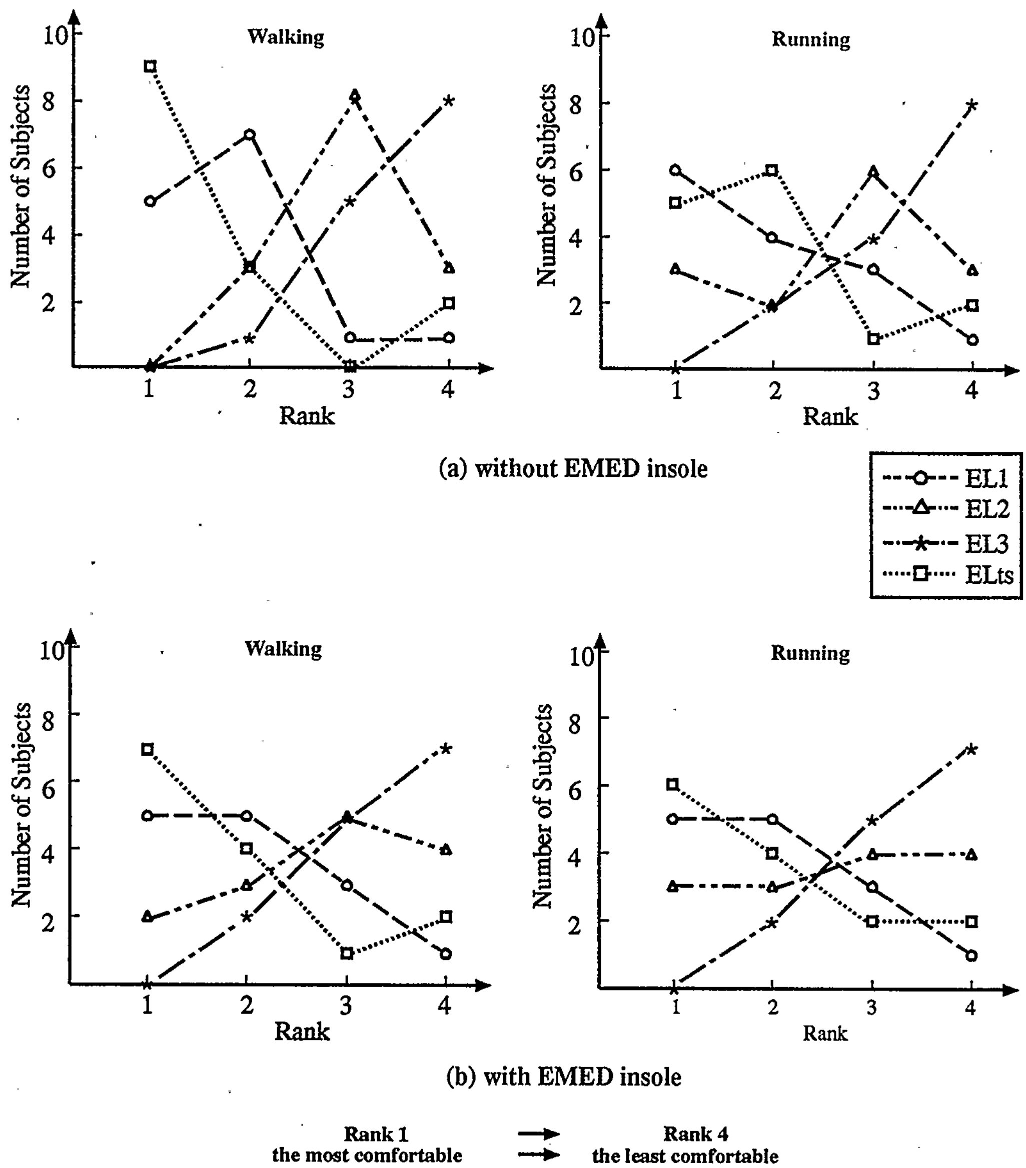


Figure 4.2. Comfort ranking of insoles

- Insole EL2 was more comfortable than insole EL3.
- Insoles EL1 and ELts were more comfortable than insoles EL2 and EL3.
- There was no significant difference in comfort rating between insole EL1 and insole ELts.
- The least comfortable insole was EL3.

However, no insole was reported to be of discomfort.

4.3.2 Pressure and Force Testing

4.3.2.1 Plantar Pressure Distribution for Four Test Insoles

The results for the pressure measurements of the four test insoles for walking are summarized in Fig. 4.3 through Fig. 4.6.

These figures show the mean values and standard errors of peak pressure (Fig. 4.3), pressure-time-integral (Fig. 4.4), maximal force (Fig. 4.5) and force-time-integral (Fig. 4.6) in eight areas of the foot.

The results showed that there was no significant difference in pressure and force in the areas of the rearfoot, medial midfoot and lateral forefoot between the four test insoles.

In the lateral midfoot, all the pressure and force variables were found significantly higher for insole ELts than for the other three insoles. The peak pressure and pressure-time-integral was significantly lower for insole ELts in medial forefoot. No significant differences were found between insole EL1, EL2 and EL3 in both lateral midfoot and medial forefoot areas.

The peak pressure, pressure-time-integral and maximal force at hallux for insole ELts were significantly smaller compared with those for insole EL3. The peak pressure and the force at the proximal phalanges produced by the insole ELts were significantly larger than the forces produced by insole EL1 and insole EL2.

The results for running are shown on Fig. 4.7 and Fig. 4.8. These figures demonstrate the mean value of peak pressure (Fig. 4.7) and pressure-time-integral (Fig. 4.8) in each area of the foot for the test insoles.

In general, for running movement, there were no significant differences in peak pressure and pressure-time-integral in the areas of rearfoot, lateral midfoot and medial forefoot between the four test insoles. The peak pressure and pressure-time-integral in the medial midfoot was significantly smaller for insole EL1 than for insole EL2 and ELts. Peak pressure was significantly smaller for insole ELts than for other three insoles at the lateral forefoot and the hallux. Comparing with other insoles, insole EL3 produced the highest pressure at the proximal phalanges.

4.3.2.2 Pressure Distribution for the Most and Least Comfortable Insoles

Due to the individual variation of the comfort rating of the test insoles (see Fig. 4.2), the insole with rank 1 was chosen as the most comfortable insole as well as the insole with rank 4 was chosen as the least comfortable insole for each individual subject. The means and standard errors of the pressure variables from the fourteen individual subjects were calculated and were used in the comparison between the most comfortable and the least comfortable insoles.

From statistical analysis, it can be seen that the peak pressure, pressure-time-integral and contact area were significantly smaller for the most comfortable insole compared with the least comfortable insole in the area of total foot.

The results for the pressure and force distribution variables of the most and the least comfortable insoles for walking movement are shown on Fig. 4.9 through Fig. 4.12.

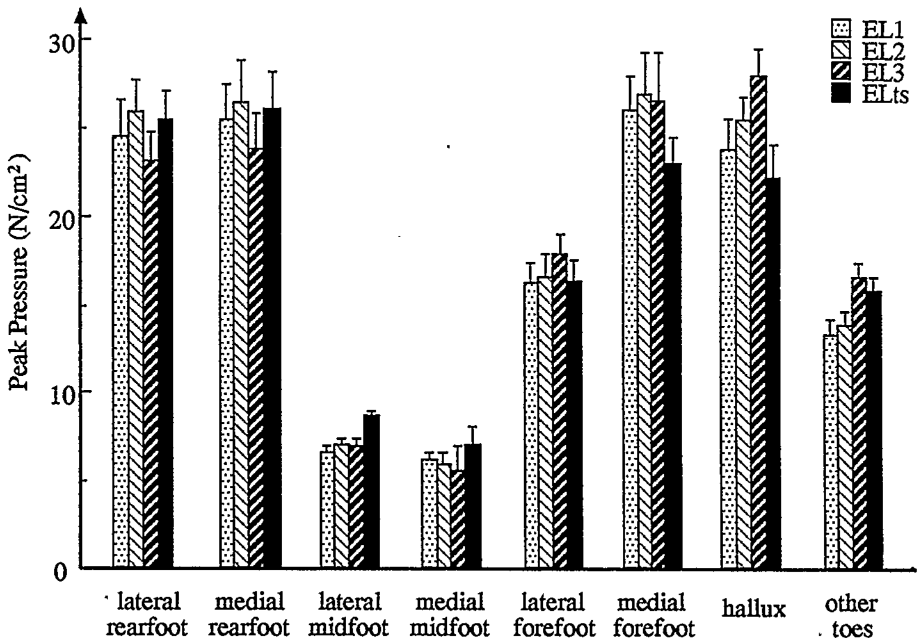


Figure 4.3. Mean and standard error of peak pressure for walking

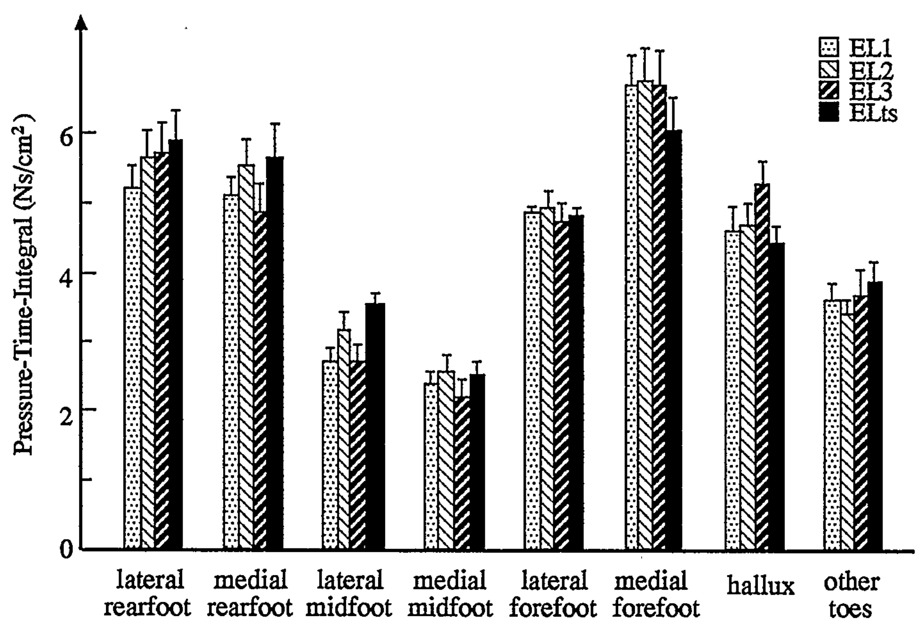


Figure 4.4. Mean and standard error of pressure-time-integral for walking

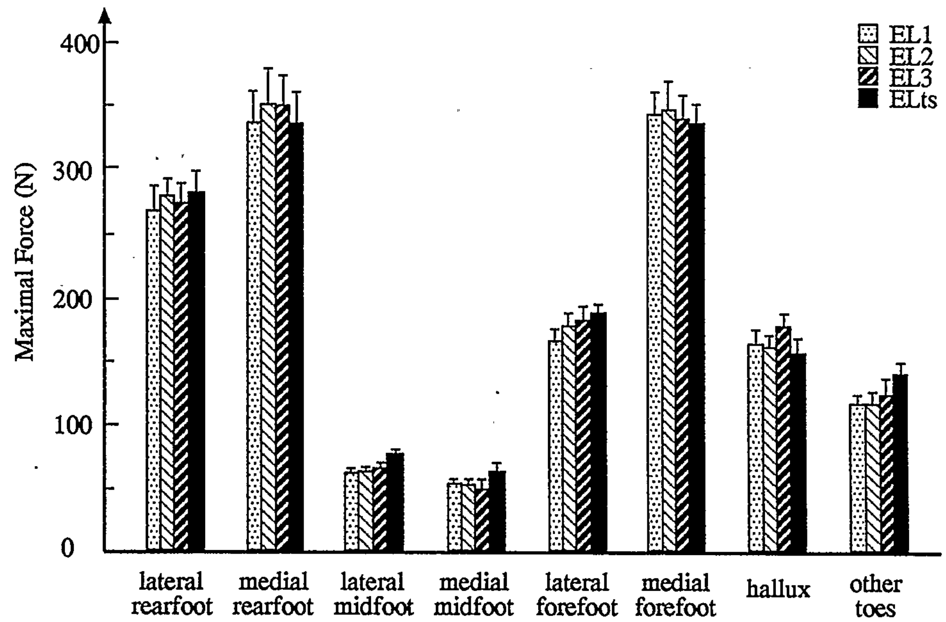


Figure 4.5. Mean and standard error of maximal force for walking

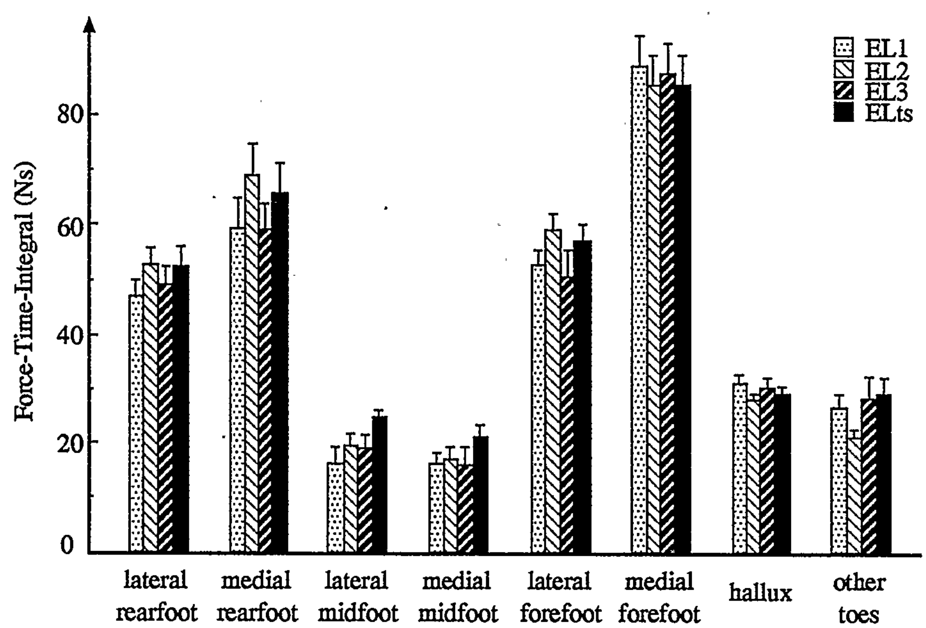


Figure 4.6. Mean and standard error of force-time-integral for walking

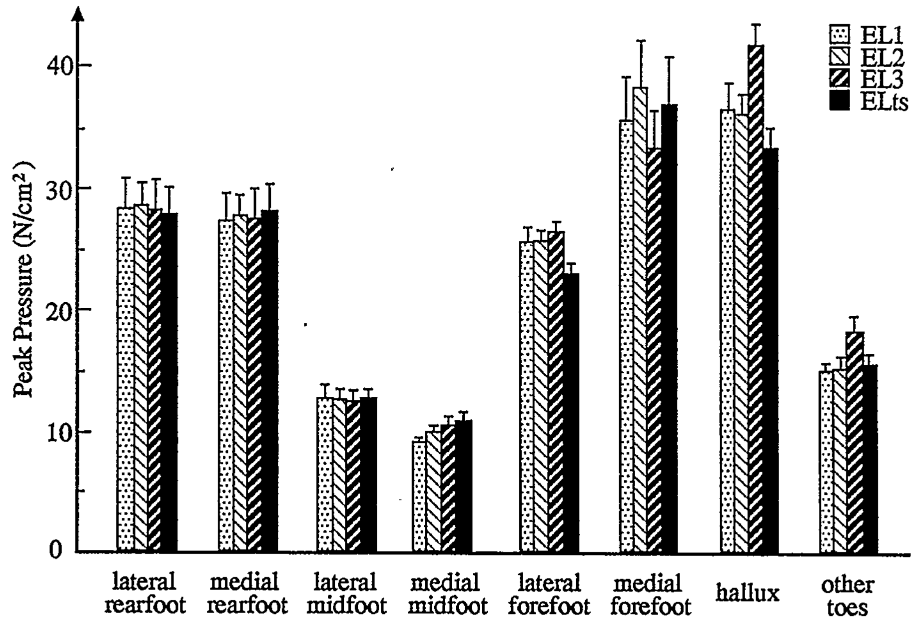


Figure 4.7. Mean and standard error of peak pressure for running

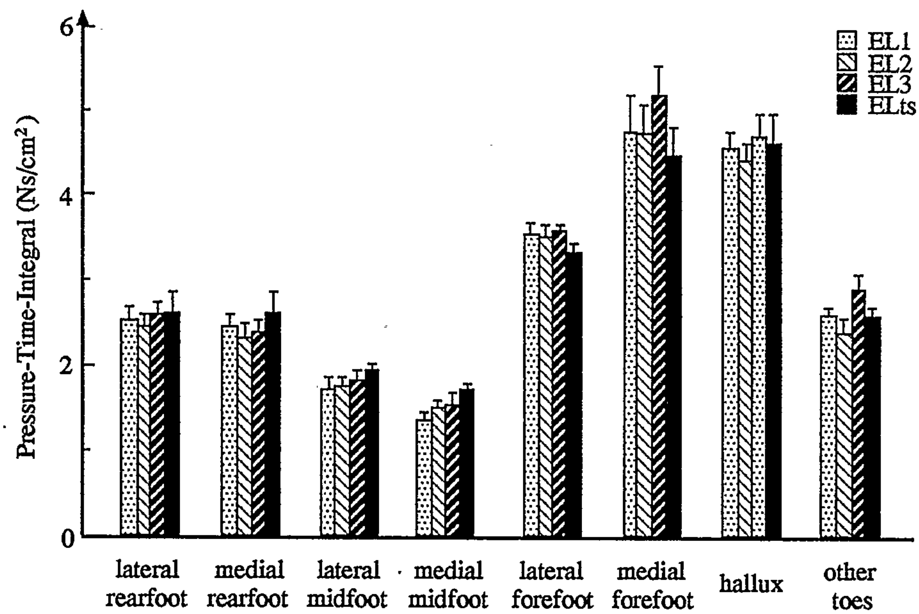


Figure 4.8. Mean and standard error of pressure-time-integral for running

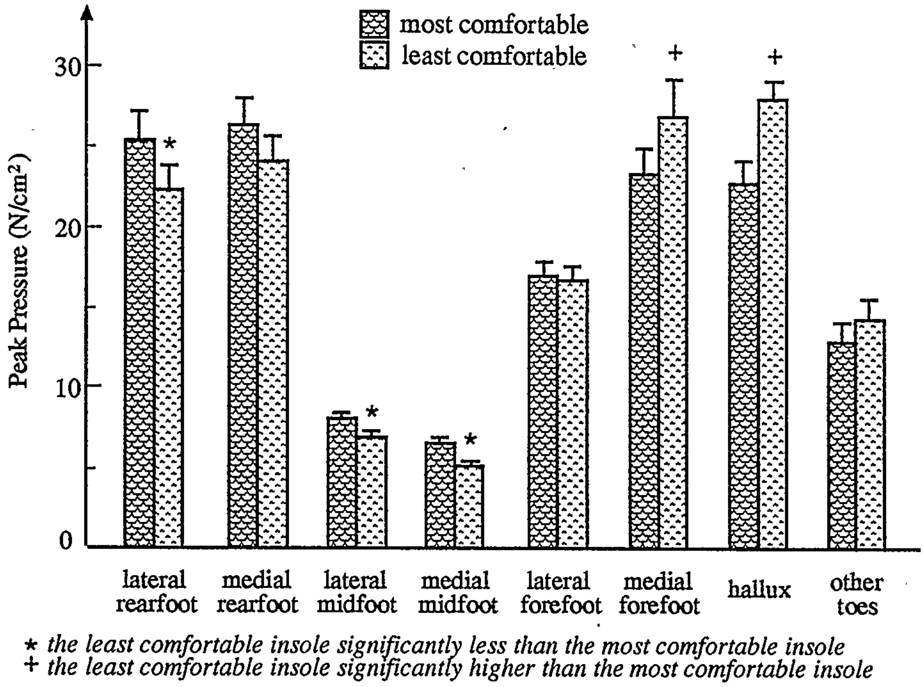


Figure 4.9. Mean peak pressure and standard error for walking

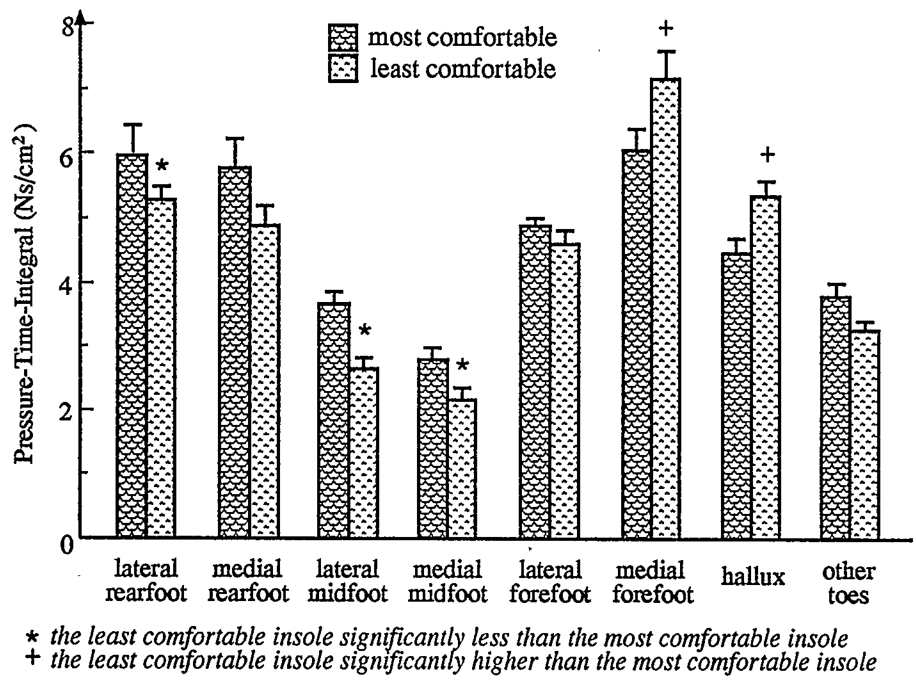


Figure 4.10. Mean pressure-time-integral and standard error for walking

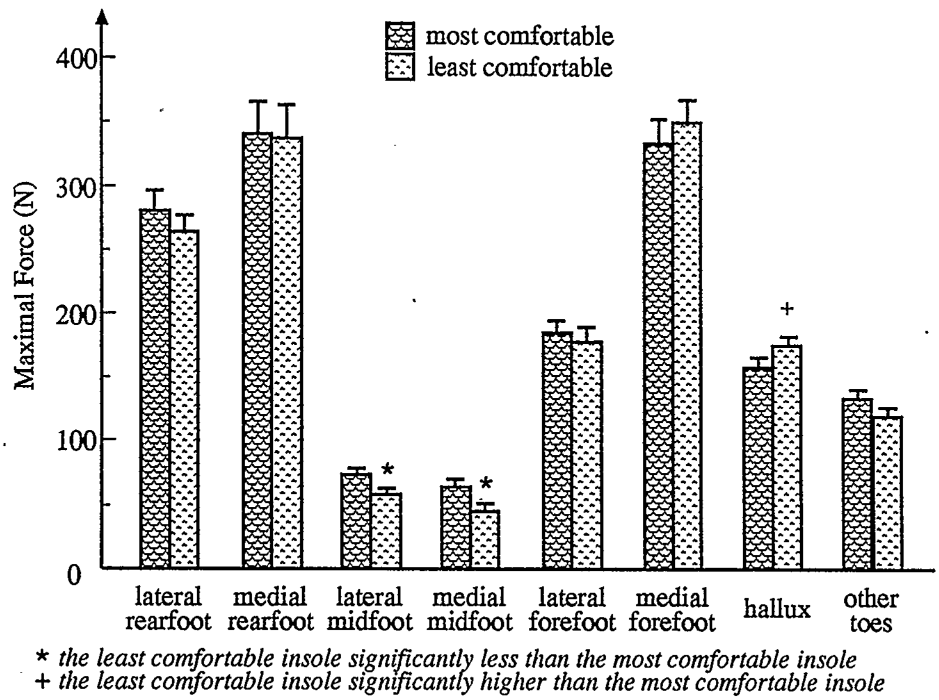


Figure 4.11. Mean maximal force and standard error for walking

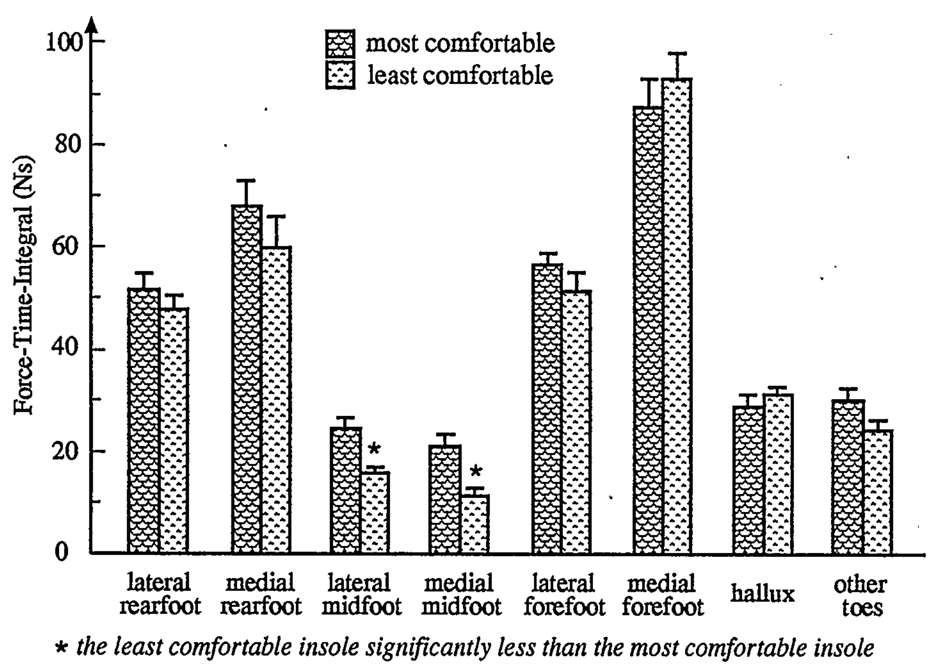


Figure 4.12. Mean force-time-integral and standard for walking

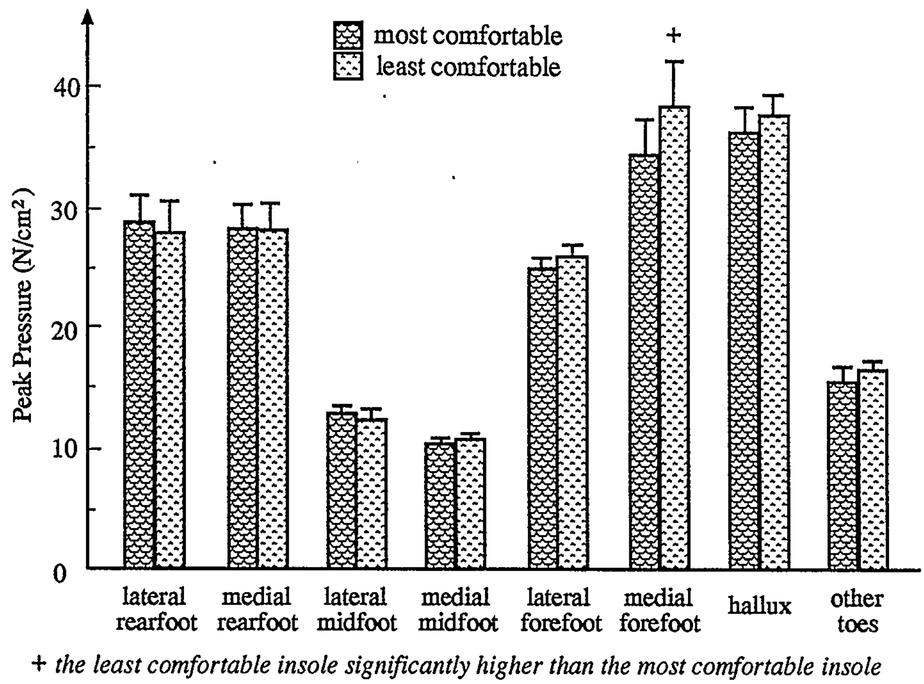


Figure 4.13. Mean peak pressure and standard error for running

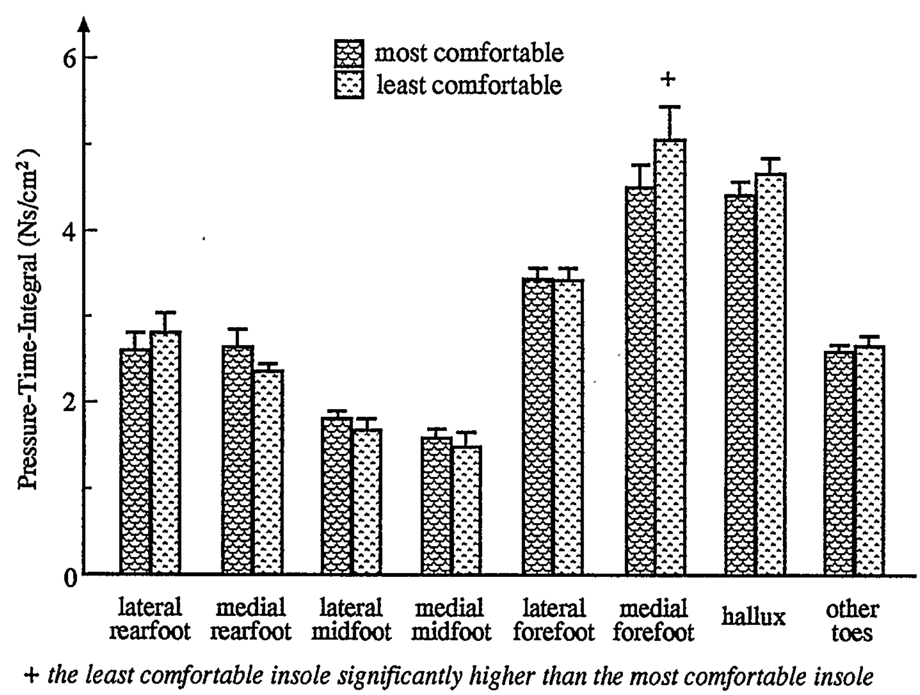


Figure 4.14. Mean pressure-time-integral and standard error for running

In the lateral rearfoot area, significant differences in peak pressure and pressure-time-integral were found between the least and the most comfortable insole. Compared with the most comfortable insole, the peak pressure was 11% lower and the pressure-time-integral was 17% lower for the least comfortable insole (Fig. 4.9 and Fig. 4.10). The force and force-time-integral for the least comfortable insole were also lower (Fig. 4.11 and Fig. 4.12), but the differences were not statistically significant. There were no significant differences between the two comfort conditions in the medial rearfoot area.

In the midfoot area, the pressure and force were significantly smaller for the least comfortable insole than for the most comfortable insole. The peak pressure for the least comfortable insole was 13% lower in lateral midfoot and 20% lower in the medial midfoot. The pressure-time-integral was 28% lower in the lateral midfoot and 22% lower in the medial midfoot for the least comfortable insole. The maximal force was 23% less in the lateral midfoot and 28% less in the medial midfoot, while the force-time integral was 37% less in the lateral midfoot and 46% less in the medial midfoot area for the least comfortable insole.

No significant differences in force were found in both the lateral and medial part of forefoot between the two comfort conditions (Fig. 4.11 and Fig. 4.12). However, significant difference in pressure was demonstrated in the medial forefoot (Fig. 4.9 and Fig. 4.10). For the least comfortable insole, the peak pressure was 16% higher and the pressure-time-integral was 18% higher than for the most comfortable insole, respectively.

A significant high pressure was found at the hallux for the least comfortable insole. The differences between the two comfort conditions were 23% in peak pressure, 20% in pressure-time-integral and 11% in maximal force, respectively. No significant difference was shown at the proximal phalanges.

Fig. 4.13 and Fig. 4.14 give the results for running. Statistical analysis showed a high load at hallux for the least comfortable insole. The peak pressure was 11% larger and the pressure-time-integral was 12% larger for the least comfortable insole than for the comfortable insole. There was no significant difference between the two comfort conditions in other areas of the foot.

Results for the maximal contact area between the plantar surface of the foot and the insole provided the following observations. All the subjects showed no differences in contact area in the regions of the rearfoot, lateral midfoot and forefoot between the two comfort conditions. The results for the contact area in the region of medial midfoot is shown on Table 4.2. It demonstrated that for all the subjests, the contact area in medial midfoot for the least comfortable insole was not larger than for the most comfortable insole for both walking and running.

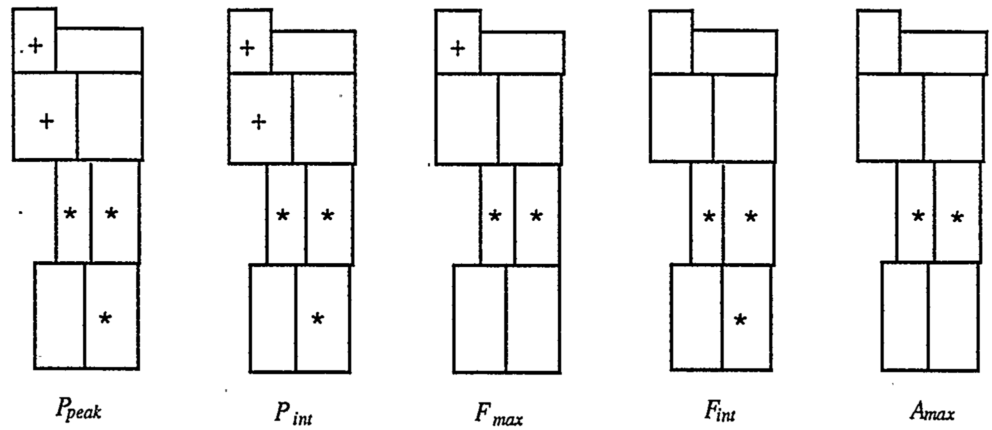
SUBJECT	MAXIMAL CONTACT AREA IN MEDIAL MIDFOOT (cm^2)			
	Working		Running	
	Mostcomfort	Leastcomfort	Mostcomfort	Leastcomfort
1	22	16	23	22
2	21	18	23	21
3	19.5	19	23	23
4	22	18	23	22
5	22	20	23	22
6	21	19	23	23
7	21	5	20	16
8	17	12	22	17
9	20	17	23	20
10	20	18	23	19
11	20	16.5	23	11
12	22	18	23	22
13	21	18	23	21
14	18	6	20	16
MEAN	20.46	15.75	22.5	19.64
SD	1.53	4.73	1.09	3.48
SE	0.41	1.27	0.29	0.93

Table 4.2. Illustration of contact area in medial midfoot

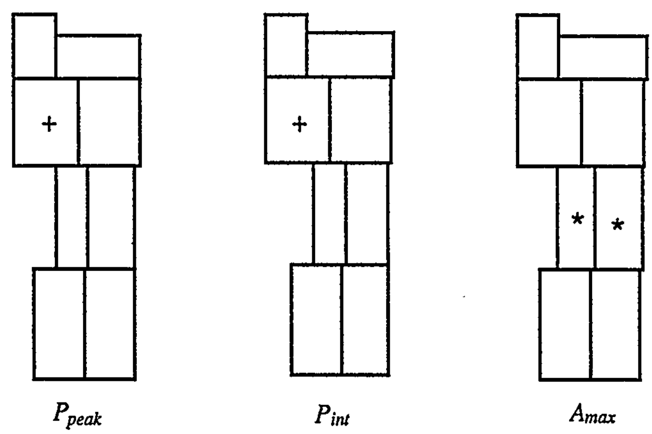
A summary of the significant differences in the above mentioned variables between the least comfortable insole and the most comfortable insole is given in Fig. 4.15. From this figure, it can be seen that the pressure or force shifted from the midfoot to the forefoot and caused a high loading at the lateral forefoot and the big toe with wearing the least comfortable insole.

4.3.2.3 Center of Force Path for the Most and Least Comfortable Insoles

Differences in center of force were found in the lateral-medial direction of the foot. Fig. 4.16 and Fig. 4.17 present the results from one subject. Eleven out of fourteen subjects showed that the center of force for the least comfortable insole was located on a more medial side of the foot in the middle phase of a gait (Fig. 4.16). Two subjects showed no difference between the two conditions. The biggest difference in x coordinate between the two insole conditions was 0.8 cm (Fig. 4.16). There was no significant difference in center of force in the longitudinal direction between the two conditions (Fig. 4.17).



(a) Walking



(b) Running

* *the least comfortable insole significantly less than the most comfortable insole*
+ *the least comfortable insole significantly higher than the most comfortable insole*

Figure 4.15. Significant differences for the variables between the least and the most comfortable insoles

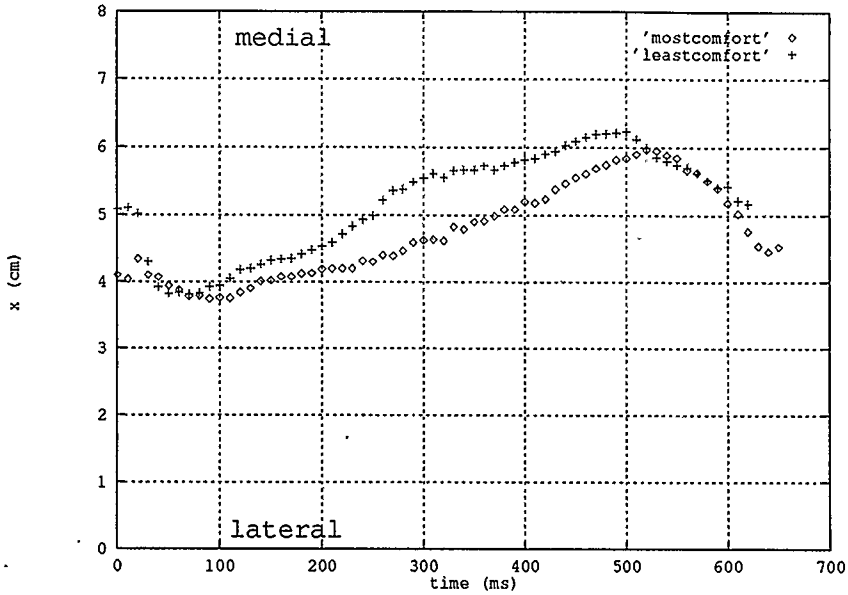


Figure 4.16. Center of force path in transversal direction for walking

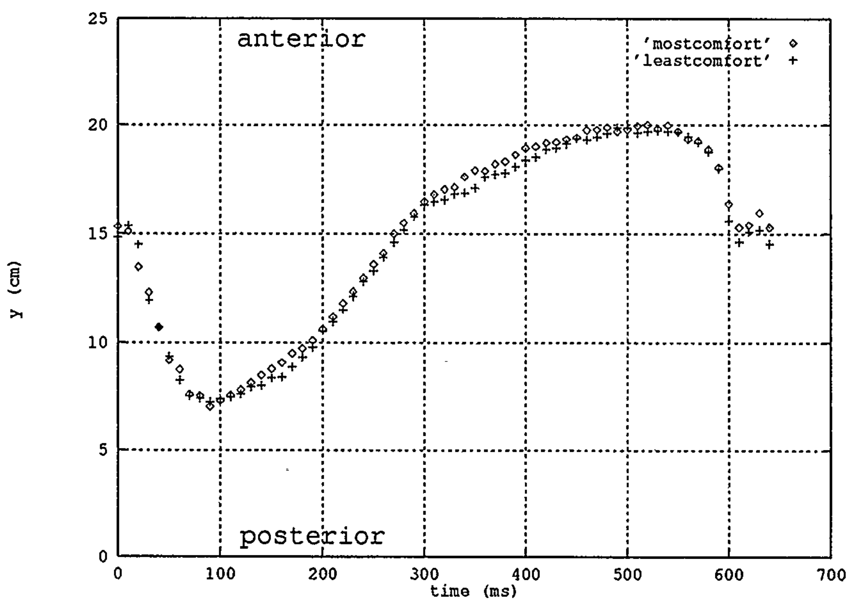


Figure 4.17. Center of force path in longitudinal direction for walking

4.4 DISCUSSION

The results for the ranking in comfort of the insoles indicated that different shoes may be rated differently with respect to comfort by different athletics. The comfort feeling depends on the individual characteristics (e.g. anatomy, skeleton of the foot). A shoe which is comfortable for one athletic can be less comfortable for another one. This result is also supported by Seydel's study [73].

Statistical analysis for the rating of comfort showed that insole EL3 was the least comfortable insole for both walking and running. Compared with other insoles, insole EL3 was very hard and unflexible. This suggested that cushioning and flexibility of a shoe sole may be the important factors for running shoe comfort.

The different results in ranking of the test insoles between walking and running indicated that the feeling of shoe comfort might be related to the movement the subject performed. In comparison with walking, the differences of average rating between the four insoles were smaller for running. It suggests that plantar pressure distribution was more sensitive to the change of the comfort during walking than during running.

By inserting an EMED insole, the rank distribution of the test insoles changed for the walking movement, but did not change for the running movement. It is suggested that running could be not sensitive to the influence of the EMED measuring insole. However, it is of importance to consider the influence of the pressure measuring insole on the feeling of comfort when measurements of the pressure distribution inside the shoe are used to study comfort during walking.

The results of the pressure measurements displayed a big difference between the most and the least comfortable insoles for walking. For the least comfortable insole the pressure and force were significantly higher in the forefoot area and significantly lower in the areas of midfoot and heel. The contact area in the midfoot was smaller for the least comfortable insole than for the most comfortable insole. Similar differences in presure distribution were also found as comparing insole EL3 with other insoles, which were statistically more comfortable than insole EL3.

The above results seem not in agreement with the study performed by Hamilton et al [29]. They reported that the force was significantly higher in the midfoot area and the pressure was higher at the heel for the less comfortable shoe compared with the comfortable shoe. The contact area was larger for the less comfortable shoe. These conflictions could be caused by the construction of the shoes. In Halmilton's study, the comfortable and less comfortable shoes were brought by the subject himself and most of them were street shoes. This kind of shoe is relatively stiff and has relatively low heel height compared with running shoe. It is assumed that these factors cause a high loading in the rearfoot area and a small contact area in midfoot. By reducing the pressure at the heel, the pressure can distribute more evenly at the plantar surface of the foot for comfort.

In this study, standardized running shoes were used. Compared with street shoes, running shoes can provide more support in the midfoot area and more cushioning. The results for this study showed that the peak pressures for the least comfortable insole were much higher in the medial forefoot and hallux than in the rearfoot. This high pressure in the forefoot area might produce some sensory stimulation which resulted in a decrease in comfort. However, for the most comfortable insole the peak pressure had little difference between medial forefoot, hallux and rearfoot. This indicated that the lower loading in the medial forefoot and hallux for the most comfortable insole led to a reduction of the peak pressure and to a more even pressure distribution at the plantar surface of the foot. It is proposed to be a direction to determine the comfort of running shoe.

For the running movement, no significant differences in force and pressure were found in most of areas of the foot between the two comfort insole conditions. The peak pressure and pressure-time-integral at the medial forefoot area showed similar results with for walking. The results for running indicated that present pressure measurements might not sensitive enough for detecting change of comfort if the difference in comfort level between the shoes was not large enough.

Looking at the functions of the pressure and force variables, the results indicated that all the variables were relevant and provided the same trend of change with change of insole condition. The peak pressure and pressure-time-integral were more sensitive to the change of the comfort conditions than maximal force and force-time-integral. Therefore, pressure variables at different foot areas could be used to reflect the difference in pressure distribution at the plantar surface of the foot produced by changing shoe comfort conditions.

In general, pressure distribution between the plantar surface of the foot and shoe can detect the comfort of running shoes for the walking movement. Comfortable running shoes should provide pressure distribution leading to low and well-distributed pressures at the plantar surface of the foot.

CHAPTER 5

INFLUENCES OF SENSORY INPUT ON PLANTAR PRESSURE DISTRIBUTION

5.1 INTRODUCTION

During normal locomotion, the foot is the connection between the human body and the earth. It is a unique, intricate mechanism which has a wide variety of functions: (1) to cushion the body and support the locomotor system; (2) to transmit forces between the ground and the musculoskeletal system; (3) to adapt to uneven surfaces; (4) to keep the body in balance, and (5) to serve as a sensor which perceives loads (body weight and external forces), balancing status, and other sensory input to the foot and adjust the disturbed body position to a new stable position through the nervous system [47] [48] [61]. The supporting and force transferring functions of the foot are evident and are well discussed in the literature, whereas less research has been published on the influence of sensory input on the force under the foot.

The sensory feedback control system plays a central role in human locomotion [48] [65]. Disorders impairing sensory perception may cause serious injuries. When plantar sensation of impact are attenuated, humans underestimate impact and reduced impact-moderating behavior. This has been suggested to cause chronic overloading related with injuries [65].

On the other hand, interference with any sensory change by disease, or stimulation from outside will certainly cause a disturbance of posture and an adjustment of the body to its correct attitude and influence the locomotive activities [48]. This adjustment of the body supposes to cause a redistribution of the force or pressure at the plantar surface of the foot. Using discrete capacitance transducers, Bauman and Brand measured the pressure at selected areas under the normal and anesthetic feet during barefoot walking [7]. For the anesthetic feet, the pressure under the fifth metatarsal head increased and reached a peak of more than 80 kPa during the take-off phase. They suggested that this peak was excessive and dangerous for people with anesthetic feet. A few studies concerning pressure distribution in the diabetic foot have found that the insensitive feet had abnormally high pressures under the forefoot and midfoot. A decrease in toe loading was also found with increasing neuropathic involvement [9] [21] [67] [79] [84]. Another study found that the peak pressure was lower for the subjects with normal feet than for patients with the painful heel pad (PHP) syndrome during gait [37]. Results regarding vertical impulse (pressure-time integral) showed that PHP patients had a significant decrease in hindfoot impulse and a significant increase in midfoot impulse. Soames found higher peak pressures in the areas of rearfoot, midfoot and lateral forefoot and lower pressure at the toes for walking in barefoot [77]. Results of a pilot study on the effect of sensory input (stimuli and anesthesia in the dorsal area of the foot) showed an increased force under the midfoot during a specific skiing movement - knee bending, when sensory input was changed, if compared to normal [54]. A test with ski boots showed a similar result with force under the midfoot increasing 100% to 200% from a low end ski boot, which was assumed to have limited functional and comfort properties, to three other high end ski boots, which were considered to have better functional quality [52]. From the result of these studies, it is suggested that there may be a change in plantar pressure or force distribution with a change of the sensory condition.

The purpose of this study was to examine the effect of sensory input on the pressure distribution at the plantar surface of the foot during normal walking and heel-toe running.

5.2 METHODS

Subjects, Test Shoes and Test Movements

Ten male subjects volunteered to participate in this study. All subjects were physically active and free of pathology in the lower extremity. The foot size of the subjects was 9. The subjects ranged in age from 23 to 41 years old (mean=29.2, SD=5.3), in height from 175 to 183 cm (mean=178.7, SD=2.3), and in mass from 62.5 to 75 kg (mean=67.7, SD=3.9). Identical lab running shoes were used for this study. The subjects were instructed to perform two movements: normal walking and heel-toe running.

In order to eliminate the influence of the walking and running speed on the pressure distribution of the foot [19] [39], each subject was asked to walk and run on a treadmill with a selected speed for each trial and for each of the sensory input conditions. The speed was 6 km/h for walking, and 13 km/h for running.

Sensory Inputs

Four sensory conditions were involved in this study. Three pairs of specially made "sand socks" were used to increase the sensory stimuli to the plantar surface of the foot. One type of sock, called a coarse sand sock, was constructed by gluing coarse gravel (diameter: 5-6mm) to the bottom of the sock. A second sock, called a midfoot sand sock, had the same size gravel in the middle area of the bottom of the sock and was used for stimulating the planter midfoot area. The third sock, called a small sand sock, was made of the smaller size gravel (diameter: 2-3mm) glued to the bottom of the sock. The corresponding sensory input was, therefore, referred to as "coarse", "mid" and "small", respectively. The gravel was inside the socks and made a direct contact with the plantar surface of the foot. The "normal" sensory condition was defined when the subject wore normal socks. Each subject performed the two test movements in each of the four sensory conditions.

Data Collection

Data was collected by using a flexible pressure measuring insole (EMED). The sampling frequency was 100 Hz. During the data collection, the EMED insole was inserted between the plantar surface of the foot with the sock and the shoe insole. Only the left foot was tested. The order of the testing sensory conditions was "normal", "mid", "small" and "coarse". Three trials for walking and five trials for running were collected for each subject in each experimental condition. The comments from the subject on the sensation produced by the socks were recorded after the data collection.

Data Analysis

Data was analized by using the EMED software. The foot was divided into eight areas: lateral and medial heel; lateral and medial midfoot; lateral and medial forefoot; hallux and proximal phalanges (see Fig. 5.1). These areas were created to fit each of the subjects.

Maximal force, peak pressure, pressure-time-integral, force-time-integral and maximal active area were used for data analysis. The definition of these variables were:

F_{max} = maximal force

P_{peak} = peak pressure

P_{int} = pressure-time integral or pressure impulse

F_{int} = force-time integral or force impulse

A_{max} = maximal contact area

All the above variables were used to analyze the data for walking. Because of large systematic errors (15-22%) in force measurements for running by using the EMED

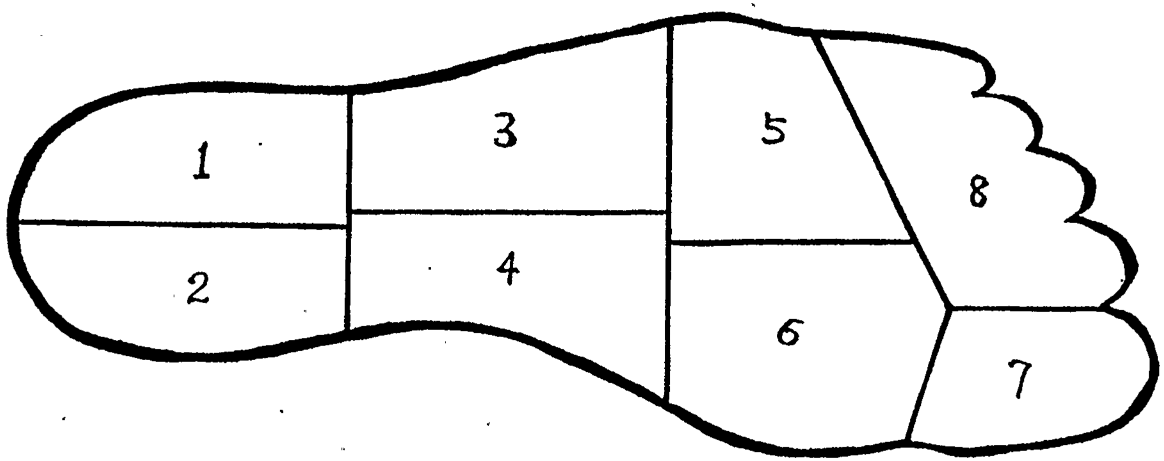


Figure 5.1. Division of the foot

1. lateral rearfoot 2. medial rearfoot 3. lateral midfoot 4. medial midfoot
5. lateral forefoot 6.medial forefoot 7. hallux 8. proximal phalanges

insole, only P_{peak}, P_{int} and A_{max} were used in the data analysis for running. The mean values of these variables for ten subjects and their standard errors were calculated for the analysis. A paired t-test was used to compare the variables between the different sensory conditions. Significance was defined when $P < 0.05$.

5.3 RESULTS

5.3.1 Subjective Assessment of the Four Sensory Conditions

All subjects felt strong stimulation at the plantar surface of the foot with increasing the sensory inputs. The results based on a questionnaire provided the following comments:

- The "coarse" sand sock produced the most intense stimulus and was very uncomfortable comparing to other sensory input conditions.
- The "normal" condition was the most comfortable comparing to other three sensory conditions.
- There was no significant difference in stimulus intensity between the "mid" and "small" sensory input conditions. They were slightly uncomfortable.

5.3.2 Pressure Distribution under the Foot during Walking

Statistical analysis showed that the pressure and force inpulses in the area of total foot were significantly increased with increasing sensory input.

The results for the pressure measurement in the eight foot regions during walking in the four sensory conditions are provided in Fig. 5.2 through Fig. 5.5. These figures show the mean values and standard errors of peak pressure (Fig. 5.2), pressure-time-integral (Fig. 5.3), maximal force (Fig. 5.4) and force-time-integral (Fig. 5.5) for the eight areas of the foot.

The results of statistical analysis showed that there were no significant differences in peak pressure and maximal force between the four sensory conditions in both lateral and medial aspects of rearfoot. In the lateral rearfoot, the pressure and force impulses were significantly increased with the "mid" sensory input. The changes

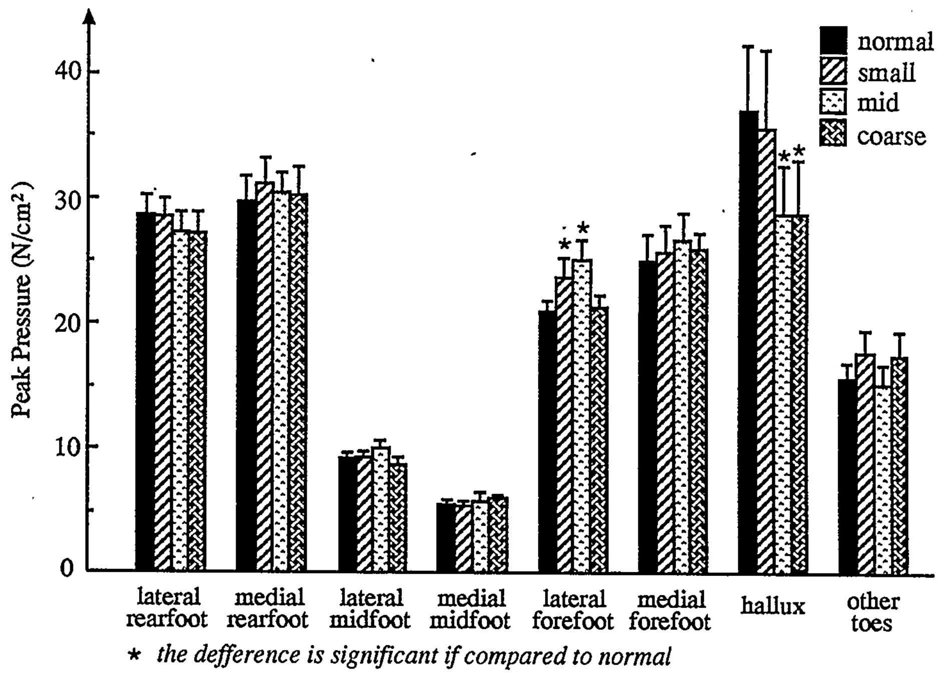


Figure 5.2. Mean and standard error of peak pressure during walking

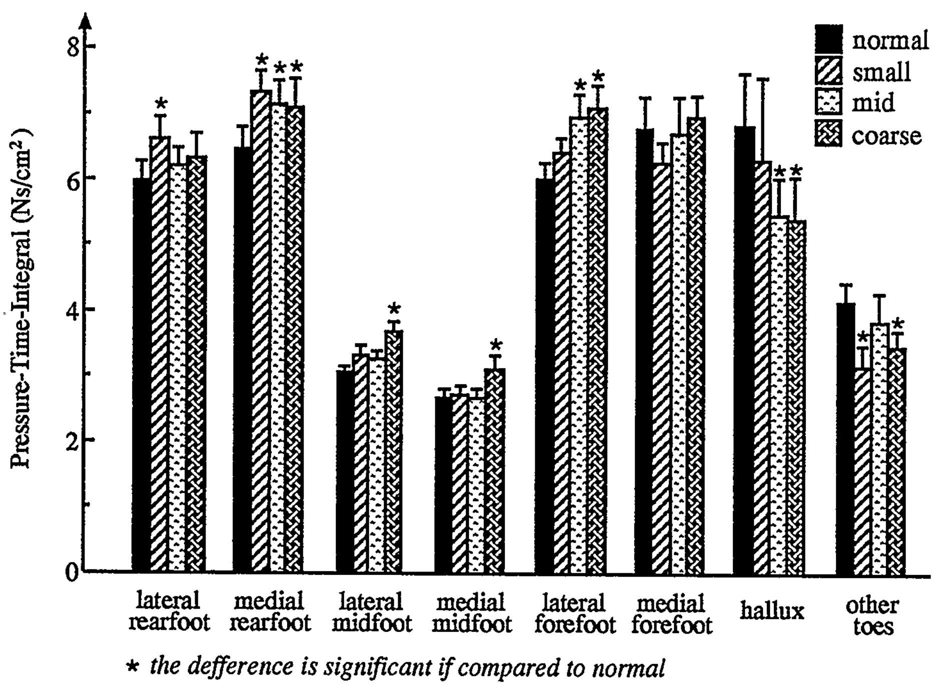


Figure 5.3. Mean and standard error of pressure-time-integral during walking

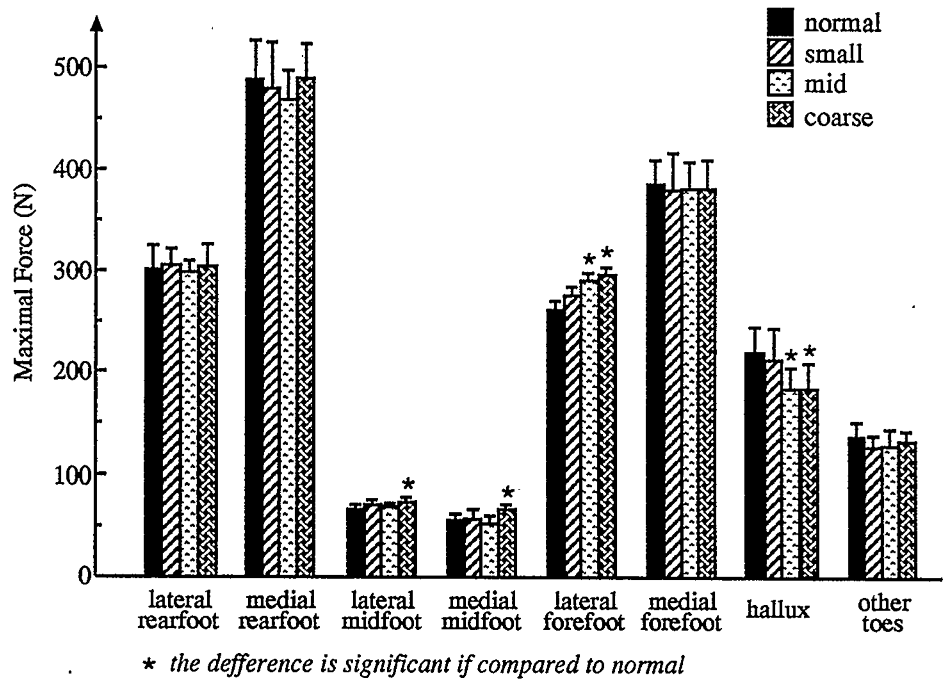


Figure 5.4. Mean and standard error of maximal force during walking

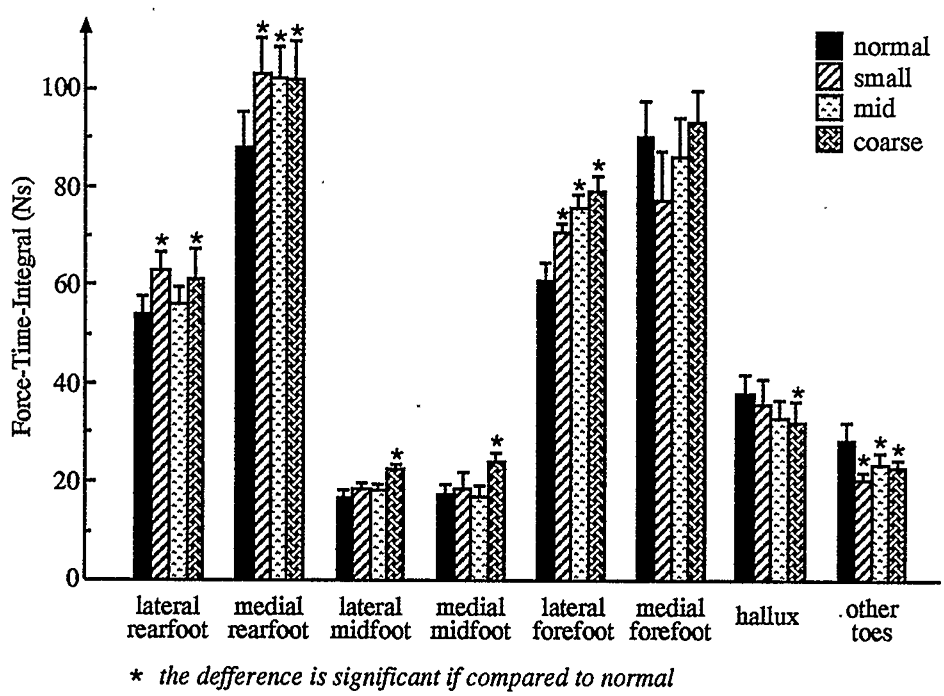


Figure 5.5. Mean and standard error of force-time-integral during walking

were 10.7% for pressure impulse, and 16.2% for force impulse, compared to normal condition. Significant positive changes in force and pressure impulses were shown in the medial rearfoot area with increasing sensory inputs. Comparing with normal sensory condition, the average increase in the pressure impulse was 13.7% with "mid" sensory input, 10.7% with "small" sensory input and 9.6% with "coarse" sensory input, respectively. The increase in the force impulse was 17.3% with "mid" sensory input, 15.9% with "small" sensory input.

In the midfoot area, there were no significant differences in force and pressure between the normal, "mid" and "small" sensory conditions. However, with "coarse" sensory input, both the pressure and force were significantly increased. In the lateral side of the midfoot, the increase was 21.0% in pressure-time-integral, 34.8% in force-time-integral and 11.7% in maximal force, separately. In the medial side of the midfoot, the increase was 17.9% in pressure-time-integral, 39.5% in force-time-integral and 21.4% in maximal force, separately.

Statistical analysis of force and pressure yielded no significant differences between the four sensory conditions in the medial forefoot area. Significant positive changes of force and pressure in the lateral forefoot were produced by increasing the sensory input. The significant change in pressure impulse was 16.3% for "small" and 18.9% for "coarse"; in peak pressure was 14.0% for "mid" and 20.6% for "small"; in force impulse was 15.0% for "mid", 24.3% for "small" and 30.2% for "coarse" as well as in maximal force was 13.8% for "small" and 16.7% for "coarse".

The pressure and force in the toe area showed negative changes in pressure and force. Comparing with normal sensory condition, decreases of 21-23% in pressure and 15-17% in force were found at the hallux when wearing the "small" and "coarse" sand socks. The pressure and force impulses at proximal phalanges decreased significantly due to the increasing of sensory inputs. The change of pressure impulse was -23.6%

for “mid”, -7.0% for “small” and -16.3% for “coarse”. The change of force impulse was for -29.0% for “mid”, -16.7% for “small” and -17.6% for “coarse”.

No differences in the maximal contact area were found in the rearfoot, forefoot and toe areas between the four sensory input conditions. Only three subjects showed an increase in maximal contact area in the midfoot area by increasing the sensory input, whereas seven subjects did not change the contact area in the midfoot.

5.3.3 Pressure Distribution under the Foot during Running

The results of pressure distribution for the running are shown in Fig. 5.6 and Fig. 5.7 with mean values and standard errors of peak pressure and pressure-time-integral in the eight foot regions.

Statistical analysis showed no significant differences in peak pressure and pressure impulse in the areas of rearfoot, forefoot and proximal phalanges between the four sensory conditions. Significantly positive change in the midfoot area and significantly negative change in the hallux area were produced by increasing the sensory inputs.

In the lateral midfoot, the increase of peak pressure was 11.5% for “mid” and 9.5 % for the “coarse”, while the increase of pressure impulse was 24.0% for “mid”, and 20.4% for the “coarse”, respectively. In the medial midfoot, the significant increase of peak pressure was 10.2% for “mid” and 12.2 % for the “coarse”, while the increase of pressure impulse was 20.5the “coarse”, respectively. No significant change of pressure was found for the “small” sensory input.

In the hallux area, the change of peak pressure was -8% for “mid”, -14.0% for “small” and -12.4% for the “coarse”, while the decrease of pressure impulse was -12.5% for “mid”, and -16.0% for the “small” and 15.8% for the “coarse”, respectively.

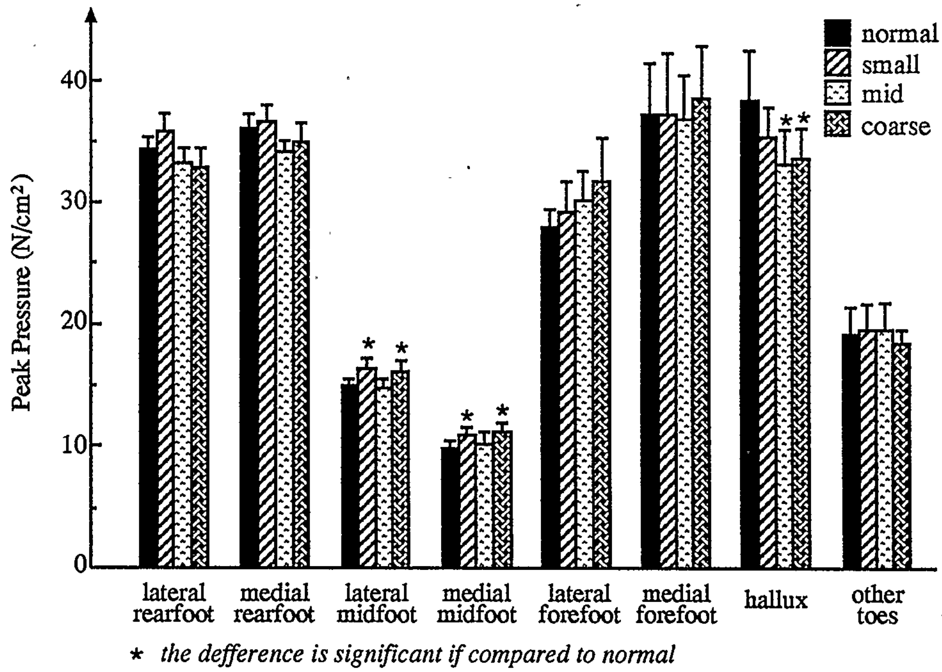


Figure 5.6. Mean and standard error of peak pressure during running

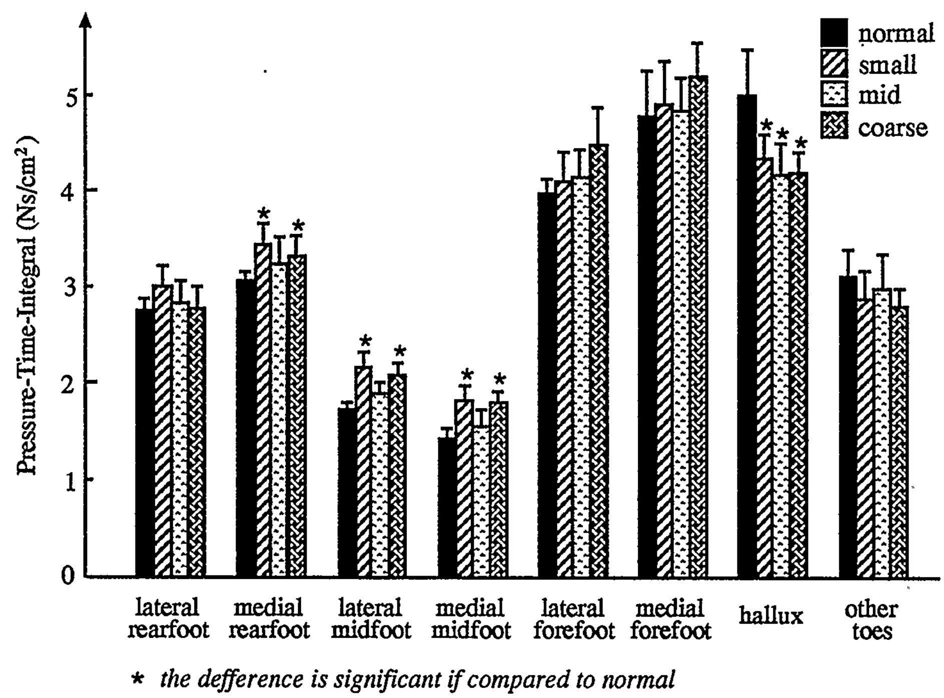


Figure 5.7. Mean and standard error of pressure-time-integral during running

5.4 DISCUSSION

The results indicated large changes in force and pressure distribution of the plantar surface of the foot between the normal and the increased sensory input conditions for both walking and running. In general, the significant changes of force and pressure by increasing sensory input occurred in the rearfoot, midfoot, lateral forefoot and toe area for walking, and in the midfoot and hallux area for running (Fig. 5.8).

For both walking and running, the force and pressure were increased in the midfoot and decreased in the toe area with the change of sensory input.

If considering insensitive foot, barefoot activities, foot disorder related pain, anesthesia, or low comfort quality of shoes as a special sensory input to the foot, the increase of midfoot loading by the sand sock sensory inputs was well consistent with the studies by Soames, Katoh and Nigg et al [37] [52] [54] [29] [77] [84]. Usually, the functional contribution of the midfoot may be considered as unimportant. However, the results in this study may suggest differently. The midfoot loading under the foot increased whenever the sensory input was functionally disturbed. It is suggested that midfoot loading may be an important indicator of sensory aspects of the foot.

It seems that there was no correlation between the increase of the midfoot loading and the site of sensory input to the foot. The sensory input could be at the heel [37], in the dorsal of the foot [54], in the midfoot (this study), or in the whole plantar surface of the foot, but the result was the same.

The increase of midfoot loading for increased sensory input seems relevant with the intensity of the sensory input for walking because the significant change of pressure and force was only for the "coarse" sensory input, which was with highest intensity and was considered as the most discomfort compared with the other two sensory input. However this interpretation is not applicable for running, in which case all the three increased sensory inputs produced significantly higher pressure in the midfoot

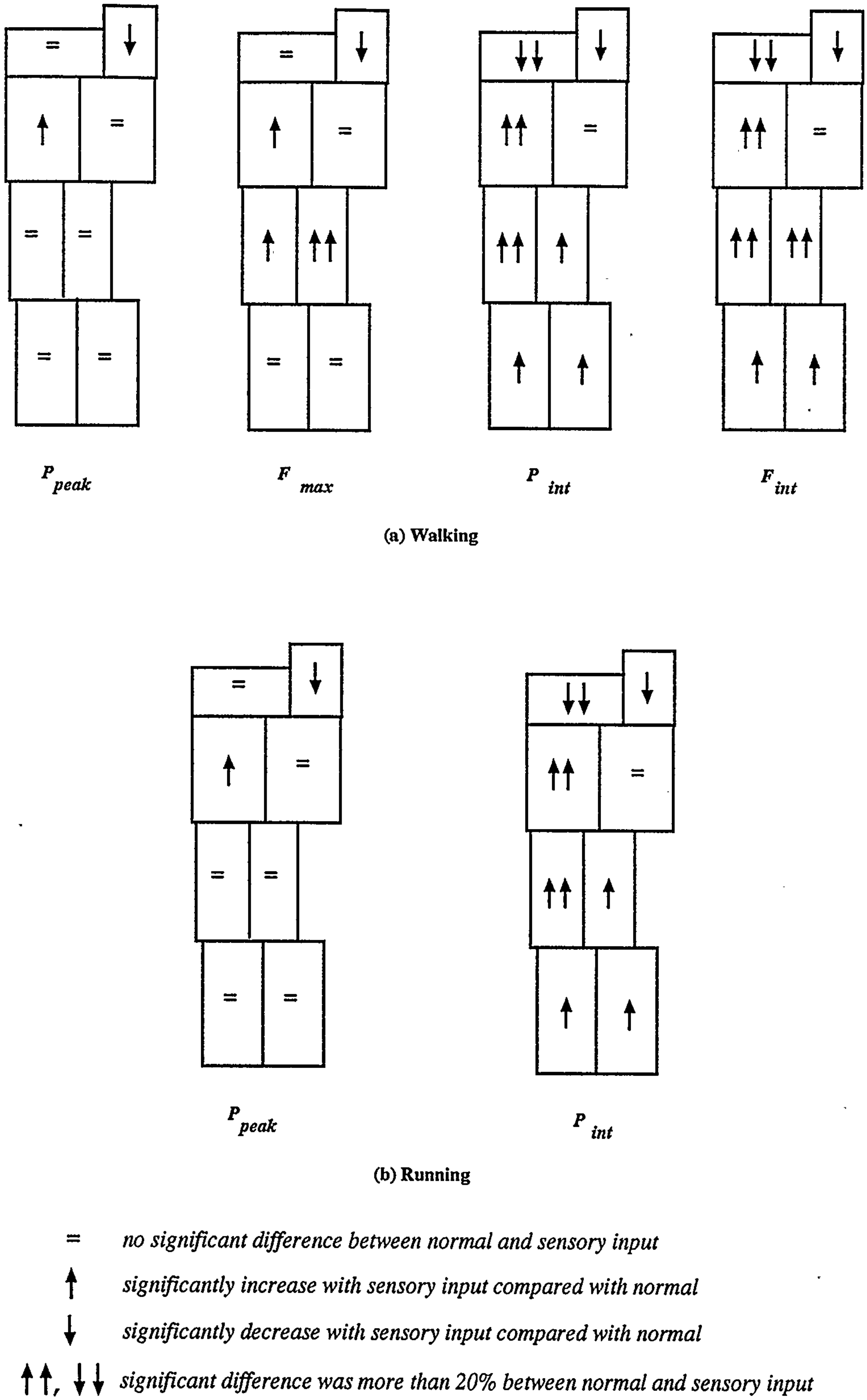


Figure 5.8. Significant differences for the variables between the increased sensory input and normal conditions

area.

The results of the increase in pressure in the forefoot and the decrease in pressure in the toe by increasing sensory input for walking corresponded the results of diabetic foot studies [9] [21] [67] [79]. It is indicated that an increase of sensory input and a decrease of sensory input may results in the same change in the plantar pressure distribution.

The results showed that the force-time-integral and pressure-time-integral were much more sensitive to the change of sensory input than the peak pressure and maximal force. This indicates that the effect of the sensory input on the pressure or force distribution were time-related. The increase of the sensory input influenced not only the maximal presure and force, but also the contact time between each region of the foot and the shoe. The force-time-integral showed the largest change for the increased sensory inputs.

For walking, the force and pressure values increased in the rearfoot, midfoot and lateral forefoot area and decreased in the toe area with the increase of sensory input. Similar results were found in the study by Soames in which the pressure was compared between walking in shoes and walking barefoot [77]. It is interesting to see that the increases of the sensory input resulted in the same pattern of changes in pressure or force distribution under the foot as barefoot walking did. Initially, barefoot walking was considered as comfortable [58], whereas the sand sock sensory input in this study was considered as discomfort. However both cases seem to increase the sensitivity of the foot. On the other hand, it has been suggested that the rate of lower extremity injuries is much lower for barefoot population than shod population. Robbins hypothesized that modern athletic footwear (due to comfort) can attenuate the perception of the load under the foot and may cause overloading related with injuries [65]. If it is true, the athletic shoe design should consider not only the comfort aspect of the shoes but also the sensory aspect of the shoes. As a matter of fact, the nervous system plays an important role in comfort. Through the nerves, external signal (stimuli) such as pressure acted on the skin of the plantar surface of the foot is sent to the sensory and control centre of the body, the brain, and produces a certain sensation [81]. The change of the pressure may indicate through the sensory feedback system and cause a change of feeling of comfort. Thus, the two aspects comfort and sensory function may be correlated in the plantar pressure distribution.

CHAPTER 6

CONCLUSION

The test of insole pressure measurement systems: Fscan and EMED in the present study showed that the EMED system had better accuracy and sensitivity for in shoe pressure measurement than the Fscan system. The present tested Fscan system was not suitable to the quantitative studies for biomechanical purpose. The EMED system could provide sufficient accuracy for the quantitative studies for walking. The force measurement by EMED system showed large error for running. However the error seemed consistent and systematic. Further study need to be done on the calibration of force measurement for running.

Pressure measurement of different shoe insoles in the present study showed high correlation between the plantar pressure distribution and shoe comfort. The pressure was lower in the forefoot and was higher in the midfoot for the most comfortable insole than for the least comfortable insole. The shift of the pressure from forefoot to midfoot for the most comfortable insole reduced the high peak pressure and provided an even distribution of the pressure at the plantar surface of the foot. The peak pressure was very sensitive to the change of the comfort conditions.

Pressure and force distribution can detect the change of sensory condition of the foot. When sensory input was increased, the pressure and force were increased in the rearfoot, midfoot and forefoot and decreased in the toes. Pressure and force impulses were more sensitive to the increased sensory input than peak pressure and force.

It seems that the results of the change of the pressure distribution under the foot by the increased sensory input did not correspond with the results by the reduction of comfort level of the insoles. However, both the increased sensory input and reduced comfort conditions caused an increase in pressure in the total plantar surface of the foot.

In the present study, the sensory difference caused by the change of the insole comfort was much smaller than the difference by increasing the sensory input and did not produce any discomfort. It is suggested that the peak pressure is an important variable to judge the comfort level of the shoes if the discomfort is not involved. For discomfort, the time-related pressure and force impulses are more important than the peak pressure.

Generally speaking, pressure measurement under the foot can indicate the change of comfort condition and may be a way to relate the definition of comfort.

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APPENDIX A

NUMERICAL RESULTS OF PRESSURE MEASUREMENTS OF THE MOST AND THE LEAST COMFORTABLE INSOLES

FOOT REGION	PEAK PRESSURE (N/cm²)			
	most comfortable insole		least comfortable insole	
	MEAN	SE	MEAN	SE
total foot	28.79	1.29	31.88	1.49
lateral rearfoot	25.36	1.73	22.46	1.32
medial rearfoot	26.29	1.86	24.07	1.58
lateral midfoot	8.18	0.27	7.09	0.29
medial midfoot	6.54	0.33	5.20	0.26
lateral forefoot	17.07	0.81	16.88	0.85
medial forefoot	23.32	1.50	27.04	2.24
hallux	22.86	1.43	28.09	1.20
proximal phalanges	12.89	1.33	14.23	1.44

Table A.1. Illustration of peak pressure for the most and the least comfortable insoles during walking

FOOT REGION	PRESSURE-TIME-INTEGRAL (Ns/cm²)			
	most comfortable insole		least comfortable insole	
	MEAN	SE	MEAN	SE
total foot	9.70	0.37	9.44	0.57
lateral rearfoot	5.97	0.47	5.26	0.23
medial rearfoot	5.80	0.44	4.89	0.32
lateral midfoot	3.67	0.18	2.66	0.16
medial midfoot	2.78	0.33	5.20	0.26
lateral forefoot	4.92	0.12	4.57	0.22
medial forefoot	6.04	0.33	7.13	0.46
hallux	4.48	0.24	5.36	0.24
proximal phalanges	3.80	0.22	3.26	0.17

Table A.2. Illustration of pressure-time-integral for the most and the least comfortable insoles during walking

FOOT REGION	MAXIMAL FORCE (N)			
	most comfortable insole		least comfortable insole	
	MEAN	SE	MEAN	SE
total foot	962.8	25.9	871.5	22.9
lateral rearfoot	279.8	16.9	262.7	15.0
medial rearfoot	340.4	25.5	338.4	25.7
lateral midfoot	74.4	3.7	57.6	3.9
medial midfoot	63.4	5.7	45.6	5.5
lateral forefoot	186.6	9.4	178.8	11.2
medial forefoot	334.5	18.2	349.6	19.7
hallux	158.2	9.8	175.2	9.2
proximal phalanges	132.1	8.3	118.1	9.0

Table A.3. Illustration of maximal force for the most and the least comfortable insoles during walking

FOOT REGION	FORCE-TIME-INTEGRAL (Ns)			
	most comfortable insole		least comfortable insole	
	MEAN	SE	MEAN	SE
total foot	383.3	12.9	332.3	14.9
lateral rearfoot	51.78	3.28	48.00	2.61
medial rearfoot	67.29	5.38	59.28	6.31
lateral midfoot	24.56	2.05	15.42	1.60
medial midfoot	21.25	2.09	11.38	1.56
lateral forefoot	56.46	2.45	51.15	4.12
medial forefoot	87.44	5.69	92.73	5.03
hallux	28.88	1.57	31.21	1.65
proximal phalanges	30.91	2.21	24.16	2.16

Table A.4. Illustration of force-time-integral for the most and the least comfortable insoles during walking

FOOT REGION	PEAK PRESSURE (N/cm²)			
	most comfortable insole		least comfortable insole	
	MEAN	SE	MEAN	SE
total foot	41.39	2.00	42.98	2.84
lateral rearfoot	28.82	2.32	28.58	2.52
medial rearfoot	28.52	2.09	28.44	2.43
lateral midfoot	13.05	0.73	12.49	3.82
medial midfoot	10.33	0.66	10.63	0.56
lateral forefoot	25.10	0.97	26.02	1.09
medial forefoot	34.66	2.86	38.36	3.90
hallux	36.46	1.91	37.79	1.73
proximal phalanges	15.69	0.80	16.52	0.90

Table A.5. Illustration of peak pressure for the most and the least comfortable insoles during running

FOOT REGION	PRESSURE-TIME-INTEGRAL (Ns/cm²)			
	most comfortable insole		least comfortable insole	
	MEAN	SE	MEAN	SE
total foot	6.26	0.13	6.51	0.27
lateral rearfoot	2.62	0.21	2.81	0.26
medial rearfoot	2.64	0.23	2.33	0.11
lateral midfoot	1.83	0.11	1.71	0.12
medial midfoot	1.59	0.09	1.51	0.10
lateral forefoot	3.47	0.12	3.46	0.17
medial forefoot	4.52	0.28	5.05	0.41
hallux	4.42	0.17	4.62	0.19
proximal phalanges	2.59	0.11	2.66	0.13

Table A.6. Illustration of pressure-time-integral for the most and the least comfortable insoles during running

APPENDIX B

NUMERICAL RESULTS OF PRESSURE MEASUREMENTS IN FOUR SENSORY CONDITIONS

FOOT REGION	PEAK PRESSURE (N/cm²)							
	normal		small		mid		corase	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
lateral rearfoot	28.67	1.48	28.52	1.47	27.40	1.51	27.20	1.65
medial rearfoot	29.74	2.06	31.24	2.05	30.40	1.52	30.20	2.12
lateral midfoot	9.10	0.37	9.27	0.37	10.00	0.47	8.80	0.39
medial midfoot	5.60	0.39	5.54	0.32	5.80	0.53	6.00	0.30
lateral forefoot	20.90	0.86	23.82	1.62	25.20	1.64	21.40	1.29
medial forefoot	25.17	2.10	25.73	2.14	26.6	2.15	26.00	1.30
hallux	37.00	5.38	35.60	6.41	28.60	3.78	28.20	4.20
proximal phalanges	15.87	1.14	17.60	1.73	15.20	1.53	17.40	1.82

Table B.1. Illustration of peak pressure in four sensory conditions during walking

FOOT REGION	PRESSURE-TIME-INTEGRAL (Ns/cm²)							
	normal		small		mid		corase	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
lateral rearfoot	5.98	0.30	6.62	0.31	6.19	0.27	6.30	0.39
medial rearfoot	6.47	0.33	7.36	0.30	7.17	0.38	7.10	0.43
lateral midfoot	3.04	0.07	3.28	0.15	3.22	0.10	3.68	0.14
medial midfoot	2.64	0.14	2.69	0.15	2.62	0.15	3.11	0.21
lateral forefoot	5.99	0.24	6.41	0.22	6.96	0.33	7.12	0.34
medial forefoot	6.77	0.51	6.26	0.32	6.73	0.54	6.92	0.36
hallux	6.82	0.81	6.55	1.26	5.42	0.59	5.32	0.68
proximal phalanges	4.13	0.28	3.16	0.30	3.84	0.46	3.46	0.25

Table B.2. Illustration of pressure-time-integral in four sensory conditions during walking

FOOT REGION	MAXIMAL FORCE (N)							
	normal		small		mid		corase	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
lateral rearfoot	302.0	21.65	311.0	16.04	296.6	11.35	303.8	20.62
medial rearfoot	488.8	39.62	480.2	45.25	469.8	28.95	489.4	34.96
lateral midfoot	66.9	2.64	69.9	4.51	68.9	3.03	74.8	3.86
medial midfoot	55.2	4.01	56.9	9.10	54.8	5.89	66.9	4.25
lateral forefoot	211.4	9.46	226.2	9.51	240.6	7.63	246.6	7.48
medial forefoot	385.0	23.45	382.2	37.52	382.8	27.00	383.8	28.85
hallux	220.2	24.24	213.0	30.28	183.0	24.14	187.8	19.27
proximal phalanges	138.5	13.05	127.6	11.31	130.8	16.04	133.2	9.75

Table B.3. Illustration of maximal force in four sensory conditions during walking

FOOT REGION	FORCE-TIME-INTEGRAL (Ns)							
	normal		small		mid		corase	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
lateral rearfoot	54.28	3.97	63.05	3.85	56.37	3.31	61.08	5.93
medial rearfoot	88.13	7.56	103.3	7.39	102.1	6.83	102.0	7.93
lateral midfoot	16.93	0.69	18.44	1.28	18.38	1.19	22.82	1.04
medial midfoot	17.24	1:87	18.79	3.09	16.78	2.00	24.04	1.85
lateral forefoot	60.81	3.64	70.52	1.06	75.60	2.74	79.16	3.17
medial forefoot	90.21	7.42	77.25	10.05	86.23	8.07	93.16	6.23
hallux	38.34	4.05	35.63	5.38	32.63	3.46	32.00	4.24
proximal phalanges	28.31	3.83	20.11	1.80	23.59	2.77	23.32	1.70

Table B.4. Illustration of force-time-integral in four sensory conditions during walking

FOOT REGION	PEAK PRESSURE (N/cm²)							
	normal		small		mid		corase	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
lateral rearfoot	34.4	1.17	35.8	1.42	32.8	1.21	32.4	1.49
medial rearfoot	36.0	1.31	36.6	1.45	34.2	1.16	35.0	1.46
lateral midfoot	14.8	0.57	16.5	0.75	14.8	0.65	16.2	1.00
medial midfoot	9.8	0.61	10.8	0.65	11.8	1.04	11.00	0.67
lateral forefoot	28.0	1.22	29.2	2.59	30.2	2.49	31.8	3.60
medial forefoot	37.4	4.41	37.4	5.37	37.0	3.81	38.8	4.53
hallux	38.6	4.22	35.4	2.50	33.2	2.98	33.8	2.51
proximal phalanges	19.2	2.26	19.6	2.12	19.6	2.37	18.6	1.09

Table B.5. Illustration of peak pressure in four sensory conditions during running

FOOT REGION	PRESSURE-TIME-INTEGRAL (Ns/cm²)							
	normal		small		mid		corase	
	MEAN	SE	MEAN	SE	MEAN	SE	MEAN	SE
lateral rearfoot	2.75	0.11	3.02	0.19	2.85	0.21	2.78	0.21
medial rearfoot	3.06	0.08	3.45	0.21	3.24	0.26	3.35	0.22
lateral midfoot	1.73	0.06	2.14	0.14	1.88	0.09	2.08	0.10
medial midfoot	1.43	0.10	1.73	0.13	1.55	0.14	1.72	0.11
lateral forefoot	3.99	0.14	4.10	0.30	4.15	0.29	4.50	0.39
medial forefoot	4.78	0.49	4.90	0.46	4.87	0.32	5.22	0.36
hallux	4.99	0.51	4.37	0.26	4.19	0.36	4.20	0.24
proximal phalanges	3.12	0.28	2.88	0.30	0.38	2.81	2.81	0.19

Table B.6. Illustration of pressure-time-integral in four sensory conditions during running