THE EFFECTS OF SURFACE TYPE ON EXPERIENCED FOOT CONTACT PRESSURES AND LOWER LIMB FUNCTIONING DURING RUNNING PERFORMANCE

THESIS

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The purpose of this study was to examine the effects of different surfaces on lower limb motion and encountered pressures at two locations on the plantar surface of the right foot. Nine females performed five trials for each of four surface conditions. The results provided no evidence for surface-related changes in experienced foot contact pressures. Both asphalt and grass surfaces resulted in the shortest relative time of forefoot immobility. No surface related differences were found for the range of pronation.
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CHAPTER I

INTRODUCTION

Over recent years there has been a tremendous growth in the popularity of recreation running. Recent estimates indicate that approximately twenty-five million individuals in the United States regularly run at least five miles each week (Brody, Konecke, Day, & Kryder, 1981). Although there are definite benefits associated with participation in a running program, including the attainment of a high level of cardiovascular fitness (Saltin, 1977) and a decrease in the presence of cardiac risk factors (Martin, Haskell, & Wood, 1977), this increase in popularity has also resulted in an increase in the number of reported lower limb injuries (Brody et al., 1981; James, Bates, & Osternig, 1978; Klein, 1979). Moreover, for those individuals who persistently run long distances, the deleterious effects of any anatomic variance are magnified beyond that which would be tolerated in most other activities (James et al., 1978; Schuster, 1978).

Although a number of anatomic factors must be considered in the diagnosis and evaluation of running-related problems, there exists the contention that many of these problems are either directly or indirectly related to foot structure and
foot function during the stance phase of the activity (James et al., 1978; Klein, 1979). In terms of foot functioning, it would seem reasonable to suggest that this factor is, in turn, affected by the gait of the runner, the adopted footwear, and the terrain over which the runner moves.

Over recent years considerable attention has been directed towards understanding the biomechanical principles governing running performances (Cavanagh, Pollock, & Landa, 1977; Dillman, 1971; Penn, 1930; James & Brubaker, 1973). Investigation by Bates, James, and Osternig (1978), Jansen and Jansen (1978), Nigg, Eberle, Frey, Luett, Segesser, and Weber (1978), Payne (1978), Plagenhoef (1980), and Scranton and McMaster (1976) have shown that the gait of a runner, and in particular the speed of ambulation, changes both the location and magnitude of the experienced foot contact forces and the range of subtalar joint motion. A concern for the effects of shoe type on foot functioning has resulted in evaluations of available footwear and statements about desirable shoe characteristics (Bates, James, Osternig, & Sawhill, 1978, 1981; Ellis, 1979; Nigg et al., 1978; Plagenhoef, 1980). It would appear, however, as though few attempts have been made to examine the effects of different terrains on lower limb functioning.

Research on the characteristics of the most "efficient" surface for a given sport has provided some indirect evidence for terrain effects on encountered foot contact forces and
the forces transmitted to the leg and lower limb motion control during running (Denoth & Nigg, 1981; Ellis, 1979; McMahon & Greene, 1973; Unold, 1973 [as cited in Nigg & Denoth, 1979]) and running-related sports (Bowers & Martin, 1978). However, in none of these studies was attention directed towards specifically examining the effects of terrain on rearfoot stability, range of lower limb joint motion, and encountered pressures at selected locations on the plantar surface of the foot.

Purpose of the Study

The purpose of the study was to examine the effects of various running surfaces on foot stability and experienced pressures on the plantar surface of the foot during running performances.

Delimitations of the Study

The delimitations in this analysis of running performances over various surfaces included the following:

1. Only nine young adult females were used as subjects;
2. Only subjects who customarily wear from 7 to $8\frac{1}{2}$ sized shoes were used as subjects;
3. The running performances of each subject were evaluated on the basis of five trials for each running surface;
4. The conditions examined were limited to four running surfaces, i.e., asphalt, grass, cinder
track and rubberized asphalt. These surfaces were judged to be used by both recreational and serious runners;

5. Only one make and style of shoe was used;

6. Observations and measurements were restricted to the right lower limb.

Limitations of the Study

The limitations in the analysis of running performances on various surface types included the following:

1. Normal cinematographic analysis limitations were recognized;

2. The anatomical reference points necessary to make various computations were estimates for approximating the actual locations of these points on each subject;

3. The pressures measured were representative of the pressures exerted over the second metatarsal-phalangeal joint and the tuber-calcanei.

Definition of Terms

The following definitions are presented to clarify terms that appear in the text and might be ambiguous:

Stance phase.--The gait phase during which the foot is in contact with the ground.
Pronation.--Eversion of the calcaneous relative to the midline of the lower leg. Measurement used to approximate the true action of pronation.

Supination.--Inversion of the calcaneous relative to the midline of the lower leg. Measurement used to approximate the true action of supination.

Begin pronation.--Neutral position of calcaneous when moving from a supinated to a pronated condition.

Maximum pronation.--Position of greatest eversion of the calcaneous relative to the lower leg.

End pronation.--Neutral position of calcaneous when moving from a pronated to a supinated condition.

Maximum ankle dorsiflexion.--When the angle formed by the leg and a line through the medial malleolus and first metatarsal head assumes its smallest value.

Heel strike.--Beginning of the stance phase when the heel first makes contact with the ground. The foot is slightly supinated, the knee angle is maximum, and the leg is in front of the body's center of gravity.

Heel off.--During stance phase, the instant when the heel is no longer in contact with the ground and all support is borne by the forefoot.
Toe off.--Ending of stance phase which involves a propulsive drive forward off the toes from the leg extended behind the body's center of gravity.

First foot segment.--Section of the foot characterized by a line through the lateral malleolus and the second metatarsal head.

Second foot segment.--Section of the foot characterized by a line through the second metatarsal head to the distal phalanx of the first toe.
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CHAPTER II

REVIEW OF LITERATURE

Over recent years there has been a tremendous growth in the popularity of recreation running. Recent estimates indicate that approximately twenty-five million individuals in the United States regularly run at least five miles each week (Brody, Konecke, Day, & Kryder, 1981). Although there are definite benefits associated with participation in a running program, including the attainment of a high level of cardiovascular fitness (Saltin, 1977) and a decrease in the presence of cardiac risk factors (Martin, Haskell, & Wood, 1977), this increase in popularity has also resulted in an increase in the number of reported lower limb injuries (Brody et al., 1981; James, Bates, & Osternig, 1978; Klein, 1979). James et al. (1978) found that of the runners examined, 70 to 80 percent experienced lower extremity problems. Of these, the most frequent complaints were knee pain (29 percent), followed by shin splints (13 percent), achilles tendinitis (11 percent) and plantar fasciitis (7 percent). Support for these clinical observations has been provided by Klein (1979) who reported that knee pain and shin splints were the most frequently examined running-related injuries. In both of these investigations, it was found that 58 percent
(James et al., 1978) and 80 percent (Klein, 1979) of the runners who suffered from lower limb injuries also displayed foot abnormalities, with excessive pronation being the most commonly diagnosed. Based on the results of these studies, with supportive evidence from Schuster (1974), it can be concluded that although a number of anatomic factors must be considered in the diagnosis and evaluation of running-related problems, many of these problems are either directly or indirectly related to foot structure and foot function during the so-called stance phase of the activity. In terms of food function, it would seem reasonable to suggest that this factor is, in turn, affected by the gait of the runner, the adopted footwear, and the terrain over which the runner moves.

Prior to 1974 little attention was directed towards a biomechanical analysis of jogging gaits. The information available was either concerned with walking performances (reviewed by Cavanagh & Ae, 1980; Elftman, 1934) or sprinting and distance running at maximum speed (reviewed by Dillman, 1974; Fenn, 1930; James & Brubaker, 1973). Since that time, several investigators have examined jogging performances. In particular, attempts have been made to identify the differences between skilled and less-skilled runners. The biomechanical parameters examined included the effects of velocity on stride length (Devjathkin, 1975; Dillman, 1974; Nelson & Gregor, 1976); step rate and the vertical
displacement of the center of gravity (Miura, Kobayashi, Myashita, Matsui, & Sodeyama, 1973); the movement patterns of the leg (Miura et al., 1973; Saito, Hoshikawa, Myashita, & Matsui, 1972); and the muscular torque patterns (Dillman, 1971; Plagenhoef, 1968). In summarizing the findings of these studies, Dillman (1974) stated that "efficient" runners exhibit the following characteristics:

1. Small vertical oscillations of the center of gravity;
2. Complete hip extension during the support phase;
3. Greater knee flexion immediately following foot strike;
4. Greater knee flexion during the swing phase;
5. Maintenance of hip extension after takeoff;
6. Generally, lower stride rate and longer stride length with increasing velocity.

The functioning of the lower extremity during the stance phase of walking gaits has been subject to some scientific scrutiny. In particular, attention has been directed towards determining the nature of the foot contact pressures (Arcan & Brull, 1976; Cavanagh, 1978; Cavanagh & Ae, 1980; Cunningham, 1972; Grundy, Tosh, McLeish, & Smidt, 1975; Hennig & Nicol, 1978; Jansen & Jansen, 1978; Nicol & Hennig, 1978; Payne, 1978; Scranton & McMaster, 1976; Simon, Paul, Mansour, Munro, Abernathy, & Radin, 1981; Slocum & James, 1968). The combined results of these studies are summarized as follows:
1. Cavanagh and Ae (1980) found that the peak rear-foot pressure occurs on the rear lateral border of the heel sixty msecs after heel strike, or 17 percent into the stance phase. Grundy et al. (1975) found that this peak pressure does not occur until both the heel and forefoot are in contact with the ground;

2. Pressure magnitudes decrease at 140 msecs as the center of pressure moves anteriorly. The center of pressure moves almost directly from the heel to the metatarsal-phalangeal heads, bypassing the midfoot region (Cavanagh & Ae, 1980; Grundy et al., 1975);

3. At 220 msecs (35 percent into stance phase), simultaneous pressure concentrations exist in the heel and forefoot regions. Within 50 msecs or 40 percent into stance phase, the pressures are concentrated in the forefoot region (Cavanagh & Ae, 1980; Grundy et al., 1975; Scranton & McMaster, 1976);

4. Fifty to 55 percent into stance phase (320 msecs) the center of pressure moves beyond the metatarsal-phalangeal heads (Cavanagh & Ae, 1980). The prolonged location of forces in the forefoot region is supported by the results of Grundy et al. (1975) and Scranton and McMaster (1976);

5. Eighty-five to 90 percent into the stance phase (500 msecs) there is a slight decrease in the
magnitudes of the pressures. The pressures in the region of the metatarsal-phalangeal heads reach their highest value during the toe-off phase (580 msecs) (Cavanagh & Ae, 1980; Grundy et al., 1975; Scranton & McMaster, 1976);

6. At the conclusion of the toe-off phase (600 msecs) the pressures in the region of the metatarsal-phalangeal head decline rapidly. Pressures of small magnitude are experienced on the plantar surfaces of the first and second toe at the conclusion of the stance phase (Cavanagh & Ae, 1980; Grundy et al., 1975).

Jansen and Jansen (1978) and Payne (1978) measured the ground contact forces during walking. In both of these studies dual peak forces were recorded during the heel contact phase. These forces were found to occur at five msecs and twenty to twenty-five msecs into the stance phase. Support for these findings is provided by Cavanagh and Ae (1980); Cavanagh, Williams, and Clark (1981); Grundy et al. (1975); Scranton and McMaster (1976); and Simon et al. (1981).

As the speed of ambulation increases, the gait changes from walking to running. Studies have shown that the angular displacement in the anterior-posterior and medial-lateral direction of the lower limb segments (Bates, James, & Osternig, 1978; Nigg, Eberle, Frey, Luitl, Segesser, & Weber, 1978; Plagenhoef, 1980), the temporal characteristics of the
pressure distributions (Scranton & McMaster, 1976) and the vertical and medial-lateral contact forces (Bates, James, Osternig, & Sawhill, 1981; Bates, Osternig, Sawhill, & James, 1980; Jansen & Jansen, 1978; Payne, 1978) are speed and gait dependent. The results of these studies have shown that

1. The duration of the stance phase decreases from 580-600 msec during walking (Cavanagh & Ae, 1980; Scranton & McMaster, 1976) to 200-250 msec during running (Bates et al., 1978; Scranton & McMaster, 1976);

2. At a fast walk/slow jog pace (3-4 mi/hr) the foot initially contacts the ground on the lateral side of the heel. The angle of the foot is approximately 15° from the outside edge to the inside (in supination) and the angle between the leg and foot is slightly greater than 90° (Bates et al., 1978; Nigg et al., 1978; Plagenhoef, 1980). As the speed of travel increases, foot strike occurs on both the lateral side of the heel and the midfoot region. In addition the angle of supination and the leg-foot angle increases (Plagenhoef, 1980);

3. During jogging performances, end-supination/begin pronation occurs sometime between heel strike and 20 percent into the stance phase. This is a variable occurrence which depends on type of shoe,
physical characteristics of the runner, and running velocity (Bates et al., 1978); 

4. During jogging performances, maximum pronation occurs 35 to 45 percent into the stance phase. This is approximately at the same time that the total body center of gravity passes over the base of support and the forces are beginning to be transmitted through the forefoot as the body is propelled forward (Bates et al., 1978). Forefoot force concentrations are also found at about this relative time during walking performances (Cavanagh & Ae, 1980); 

5. At 50 to 55 percent into the stance phase, maximum dorsiflexion occurs and the forefoot loading is maintained (Bates et al., 1978); 

6. End pronation and the beginning of supination occurs between 70 to 90 percent of the stance phase (Bates et al., 1978); 

7. The relative time of occurrence of the foot contact forces and the pronation-supination events are not altered by increase in the speed of gait. However, the absolute time of each event decreases with increases in gait speed (Bates et al., 1978; Scranton & McMaster, 1976); 

8. The relative duration of the forefoot support phase increases with increases in the speed of gait (Bates et al., 1978; Jansen & Jansen, 1978; Scranton &
McMaster, 1976). In addition, the majority of the ground contact forces increase in magnitude and are concentrated in the region of the metatarsal-phalangeal heads (Scranton & McMaster, 1976).

The type of footwear worn during running performances has been found to affect foot functioning. Based on running shoe evaluations, Bates, Osternig, Sawhill, and James (1980) concluded that shoes can vary widely in both the ability to absorb the shock at heel strike and the ability to control the motion of the foot. They contend that the effectiveness of a shoe in protecting the lower leg from compressive and torsional forces varies according to individual physical characteristics, running style, and shoe design features. Support for this is provided by Nigg, Denoth, and Neukomm (1981) who demonstrated the existence of two peak forces during the heel strike phase of a running gait. The first peak was found to be associated with the retardation of the tibia (passive force) and the second to the characteristics of the muscle forces (active force). It was shown that the passive force could be modified by different shoes. The active force could be controlled by changing the running gait. The latter result has been supported by Bates, James, Osternig, and Sawhill (1981) and Plagenhoef (1980) who found that conditions which provide a high potential for severe ground contact forces, such as barefoot, hard or uneven surfaces, or poor shoes, do not produce the expected extremes in
foot-ground forces. Apparently, compensatory gait adjustments such as landing on the forefoot and greater knee flexion reduce the shock and thus keep the force of landing tolerable. However, Plagenhoef (1980) and Cavanagh and Ae (1980) contend that if the forces between the shoe and foot were measured directly rather than recording the foot-ground contact forces, the compensatory gait changes would be less pronounced and differences in shoe shock absorption characteristics would be evident.

There is evidence to suggest an inverse relationship between the shock absorbing capabilities of a shoe and the amount of pronation (Bates et al., 1978, 1980, 1981). Shoe characteristics and running style have been shown to influence this relationship. Plagenhoef (1980) demonstrated that if the shoe sole is wide/flared and made of stiff material, there is less control of pronation when the provision of extrinsic shock absorption is relatively poor. Individuals who land on their forefoot or strike the ground with relatively large forces may also cause exceptions to the relationship. Bates et al. (1980) compared a barefoot condition with a shoe that provided satisfactory motion control. The reported results were as follows:

1. Pronation began later and ended sooner for the shoe condition;
2. For the shoe condition, both the mean and relative time of maximum pronation decreased with increases in the speed of gait;

3. For the shoe condition, there was a speed-dependent trend towards a decrease in the maximum angle of pronation;

4. The mean angle of maximum dorsiflexion was less for the shoe condition than for the barefoot condition.

In conclusion, shoes have an influence on measured contact forces and foot motion, although individual anatomical structure and lower limb functioning can cause variability in the measured effects.

The characteristics of the surface over which a runner moves would appear to be another factor which can influence both foot functioning and shoe effectiveness.

McMahon and Greene (1979) examined the changes in running performance on surfaces with varying compliance. The surfaces examined were a wooden track with compliance adjustment capabilities and a surface constructed of foam rubber blocks. With more compliant surfaces, increases in both the step length and the duration of stance phase were found to occur. The stance phase time was minimal at intermediate compliances which corresponded two to four times the compliance of the musculature of the subjects.

Unold (1973) as reported by Denoth and Nigg (1981) and Nigg and Denoth (1979) found that the greatest forces were
transmitted to the ankle and knee joints during running performances on asphalt and surfaces with equivalent compliance, such as artificial turf. The smallest forces were found to occur on a grass surface. Cinder surfaces and standard gymnasium floors (cork and board) resulted in forces that were intermediate between those recorded for the asphalt and grass surfaces. This relationship between force magnitude and surface type has also been found in impact studies, one by Unold (1973) as related by Nigg and Denoth (1979) and another by Bowers and Martin (1974). In both of these investigations the acceleration of an iron ball was recorded during impacts with the examined surfaces. The results showed that both grass and similarly compliant surfaces yielded smaller accelerations and longer stopping times than did asphalt and less compliant surfaces. It was concluded that with increases in surface hardness, greater forces would be transmitted to the lower limb segments.

The influence of different shoes on surface effects were also examined in the Unold (1973) study. No significant differences in the forces at the ankle or knee joints were found among the barefoot, spike-soled shoes, thin-soled gym shoes, or soft (thick)-soled gym shoes during running performances on grass. On a hard, smooth surface, the shock attenuation capacity of the shoes played a more significant role. However, for all shoe types, the largest and smallest impact forces were recorded for the asphalt and grass surfaces,
respectively. Ellis (1979) reported testing both the impact forces between the foot and the shoe and motion control characteristics for a selection of running shoes during running performances on a treadmill, hard-packed soil, and grass surfaces. No comparative information was presented in the published report. In none of the above studies were attempts made to directly measure the foot contact pressures in the forefoot region. Recent evidence suggests that this region of the foot has an important role in the transmission of the stance phase contact forces (Cavanagh & Ae, 1980; Grundy et al., 1975; Jansen & Jansen, 1978: Scranton & McMaster, 1976).

In summary, a review of the related literature revealed that early attempts at understanding the biomechanics of running were concerned with analyses of total body motion. Based on the results of clinical studies, relationships were found between lower extremity running-related injuries and foot functioning during the stance phase of the gait. There exists evidence to suggest that foot functioning is affected by individual anatomic characteristics, speed of ambulation, shoe type, and the characteristics of the running surface. However, the effects of surface type on experienced foot contact pressures and foot functioning has received scant attention.
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CHAPTER III

PROCEDURES

The purpose of this study was to examine the effects of various running surfaces on foot stability and experienced pressures between foot and shoe during running performances.

Subjects

The subjects used in this study were nine female runners from North Texas State University (Denton, Texas) and the Denton (Texas) and Fort Worth (Texas) communities. The only requirements for subject selection were that they were between the ages of twenty and thirty-five years, that they regularly ran between fifteen and thirty miles each week, that they were accustomed to wearing shoes of the same size as those used during the study, and that they had no lower limb abnormalities or discomfort at the time of the testing sessions.

Instrumentation

Pressure Measurement Elements and Amplification System

Each subject had two pressure transducers (Model F4-4R, Hercules, Incorporated, Hercules Aerospace Division, Allegany Ballistics Laboratory, P. O. Box 210, Cumberland, Maryland 21502) adhered to the plantar surface of her right foot.
These transducers were located on the skin overlying the head of the second metatarsal-phalangeal joint and the tuber-
calcanei. Voltage changes occurring as a result of pressure exerted in the region of the transducers were transmitted via fine wires to an amplifier which was interfaced to an analogue-to-digital converter (Model 752-ADC, TransEra Corporation, Provo, Utah 84601) and a Tektronix 4052 graphics calculator (Model 4052, Tektronix Inc., Beaverton, Oregon 97005). Data sampling was initiated by a manual trigger and was continued throughout a right foot stance phase in a marked target area.

**Cinematographical Analysis**

A high speed 16 mm motion picture camera (Model DBM-54, Teledyne Camera Systems, Arcadia, California 91006) operating at 150 frames per second was used to record the performance of each subject. The camera was positioned so that the optical axis was directed towards the rear of each subject. A plane mirror was vertically oriented at 45° to the anticipated plane of motion for each subject. The experimental set-up was such that both the right lateral and rear perspectives of the right lower limb during the stance phase in a marked target area were recorded on film (see Figure 1).

Three number-coded cards were included in the field of view of the camera and filmed during each trial. The identification codes corresponded to assigned subject, surface
Fig. 1—Experimental Setup
condition and trial numbers. A linear and vertical reference was placed in the optical field of the camera to facilitate the subsequent determination of linear measurements from the film. Temporal scales were obtained by means of a timing light generator used in conjunction with the motion picture camera. Synchronization of the film and pressure records was provided by a common voltage supplied to both a channel of the analogue-to-digital converter and one of the motion picture time lights.

**Shoes**

All of the subjects performed in experimenter-provided running shoes (Etonic Transam, Etonic, Inc., Brockton, Massachusetts 02403).

**Testing Procedures**

All of the testing sessions were conducted at the North Texas State University outdoor running track in Denton, Texas. Prior to the testing sessions, the pressure transducers were calibrated according to the manufacturer's instructions. At the beginning of each testing session, measurements of each subject's weight and standing height were recorded. In addition, each subject was given instructions on the experimental procedures and asked to read and sign an informed consent form for participation. A copy of the informed consent form appears in Appendix A. Particular emphasis was placed on instructing the subject to use the same running
gait during each trial as they customarily used during training sessions. To facilitate the subsequent location of selected anatomical reference points, each subject was asked to wear shorts.

Prior to the commencement of the first trial for each subject during each testing session, three clearly visible marks were drawn on the lateral border of the sole of the right shoe. The marks were located at the heel, in line with the head of the distal phalanx of the first toe and in line with the head of the second metatarsal. Additional marks were drawn on the skin overlying the lateral projections of the right hip, right knee, and right ankle joints. A straight line was also drawn down the middle of the posterior surface of the right leg. This line extended from the lower border of the calcaneus to the popliteal fossa. The landmarks were subsequently used to determine descriptive kinematic parameters. An illustration of the selected landmarks appears in Figure 2.

Prior to the commencement of each trial, each subject was permitted to run along a section of the surface until "adjusted" to any perceived peculiarities in the condition. In addition, she practiced running along the defined runway until she could place her right foot within the marked area without making overt adjustments to her gait pattern.

Each subject performed a total of twenty trials, corresponding to five trials on each of four running surfaces. The
Fig. 2—Landmarks and Coordinate System
running surfaces were: grass, asphalt, cinder track, and rubberized asphalt. The selection of the four surfaces was based on the assumption that they represented the variety of surfaces commonly used by recreational runners. Prior to the testing sessions the camber of each surface at three locations was measured using a surveyor's transit. Each trial consisted of the subject jogging along the defined level pathway on the surface being examined.

The motion of the right lower limb when it was in contact with the marked target areas was recorded on film. Recordings were also made of the pressures exerted on the skin overlying the first metatarsal-phalangeal joint and the tuber-calcanei during the stance phase. The experimental set-up is illustrated in Figure 1.

Data Acquisition Procedures

The processed film depicting the right foot during the stance phase of each trial was analyzed with the aid of a Lafayette 16 mm stop-action analyzer (Model AAP-200, Lafayette Instrument Co., Lafayette, Indiana 47902) in conjunction with a Numonics Electronic Digitizer (Model 1200, Numonics Corporation, North Wales, Pennsylvania 19454). The digitizer was interfaced to the Tektronix 4052 Graphics Calculator. The x- and y- coordinates of the previously described landmarks, two points on the line drawn on the back of the leg above a line linking the right malleoli and two points on the line drawn on the skin over the posterior
surface of the right calcaneous were digitized and recorded for each film frame.

The data thus obtained was used in conjunction with a computer program which computed x- and y- displacements of each of the landmarks, the angle of foot pronation, the angle of inclination of the first and second foot segments, and the angle of inclination of the leg. The reference system used to determine each of the segment and joint angles is shown in Figure 2. All of the above parameters for each trial were "smoothed" using cubic spline curve fitting techniques. The temporal and kinematic values of the following instants were recorded for subsequent statistical analysis: (1) heel strike; (2) toe off; (3) maximum(s); and (4) minimum(s). Average values of the smoothed parameters were computed for each condition.

The pressure data was "smoothed," normalized by dividing by subject body mass and averaged by condition. Maximum values and integrals were recorded for subsequent statistical analysis.

**Statistical Analysis**

A statistical analysis ($p < .01$), utilizing repeated measures analysis of variance procedures was conducted to ascertain if differences exist between the conditions with the instantaneous temporal, kinematic and kinetic characteristics of the right foot stance phase entered as dependent variables.
The purpose of this study was to examine the effects of various running surfaces on foot stability and experienced pressures on the plantar surface of the foot during running performances.

Subjects

The subjects used in this study ranged in age from eighteen to thirty-seven years ($\bar{X} = 27.9$, $SD = 7.1$ years), in height from 1.61 to 1.75 meters ($\bar{X} = 1.68$, $SD = 0.01$ meters), and in weight from 51.8 to 65.5 kilograms ($\bar{X} = 58.7$, $SD = 5.1$ kilograms). The selected anthropometric characteristics of each subject appear in Appendix B.

Surfaces

The cambers of each surface expressed as elevation differences with respect to a fixed point located at the edge of each runway surface are shown in Table I.

Results

The average pressures exerted on the skin overlying the plantar surface of the second metatarsal-phalangeal joint and the tuber-calcanei are shown in Figure 3. A comparison of the records reveals that for all surface conditions, the
### TABLE I

**CAMBERS OF EACH OF THE EXAMINED SURFACES**

<table>
<thead>
<tr>
<th>Surface</th>
<th>Elevation Differences$^a$</th>
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<tr>
<td></td>
<td>O-A$^b$</td>
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<tr>
<td>Asphalt</td>
<td>5.54$^c$</td>
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<tr>
<td>Grass</td>
<td>.05</td>
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<tr>
<td>Cinder</td>
<td>.71</td>
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<tr>
<td>Rubberized Asphalt</td>
<td>1.51</td>
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</table>

$^a$All elevations measured in centimeters.

$^b$A

$^c$M of 5 measurements along runway, 1.2 m apart.
Fig. 3--Averaged Pressures over the Second Metatarsal-Phalangeal Joint and the Tuber-Calcanei.
pressures in the region of the second metatarsal-phalangeal joint were consistently greater than those experienced in the heel region. The onset of pressure in the region of the second metatarsal-phalangeal joint is also shown to have occurred later than the onset of pressure in the heel region. The duration of the recorded pressures was generally greater for the second metatarsal-phalangeal joint region than for the heel region.

The statistical analysis revealed no significant differences among the surface conditions for the maximum pressures, time to maximum pressures and mean pressures. Graphical representations of each of these variables for each surface condition appear in Figures 4 through 6. The algebraic pressure impulses experienced in the heel region for the cinder surface were found to be significantly less than those for both the asphalt and grass surfaces, $F(3,27) = 4.54$. It would appear as though these differences result from differences in both the duration and magnitude of the experienced pressures. The algebraic pressure impulses experienced in the region of the second metatarsal-phalangeal joint for the asphalt surface were found to be significantly less than those for both the rubberized asphalt and cinder surfaces, $F(3,27) = 4.14$. These results can be accounted for by significant and complementary findings for the pressure durations. That is, the pressures in the region of the second metatarsal-phalangeal joint were of lesser duration for the asphalt surface than for
Fig. 4--Maximum Pressures
Fig. 5--Time to Maximum Pressures
both the cinder and rubberized asphalt surfaces, $F(3, 27) = 5.10$. The graphical representation of the algebraic pressure impulses for each surface condition appears in Figure 7.

The mean and standard deviations for the duration of the stance phase for each condition are shown in Table II. The statistical analysis revealed that the asphalt surface stance phase duration was significantly less than those for the other surfaces, $F(3, 24) = 4.9$.

**TABLE II**

MEANS AND STANDARD DEVIATIONS OF THE STANCE PHASES

<table>
<thead>
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<th>Surfaces</th>
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<th>SD</th>
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<td>Asphalt</td>
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<td>Grass</td>
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<td>0.06</td>
</tr>
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<tr>
<td>Rubberized Asphalt</td>
<td>0.30</td>
<td>0.07</td>
</tr>
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</table>

$^a$All measures in seconds.

The angle of the right leg during the stance phase for each of the surface conditions is shown in Figure 8. The statistical analysis revealed that for both the rubberized asphalt and cinder surfaces the leg was less inclined at the instant of toe-off than it was for the other two surfaces, $F(3, 24) = 9.7$. The total range of motion during the stance
Fig. 7—Algebraic Pressure Impulses
ANGLE OF THE RIGHT LEG (SAGITTAL PLANE) DURING THE STANCE PHASE

Solid = Asphalt
Solid-Diamond = Grass
Dashed = Cinder
Dashed-Plus = Rubberized asphalt

Fig. 8 -- Angle of the Right Leg (Sagittal Plane) During the Stance Phase
phase was found to be significantly greater for the grass condition \((p < .04)\) than for both the rubberized asphalt and cinder surfaces, \(F(3, 24) = 3.1\).

The angle of the first foot segment during the stance phase for each of the surface conditions is shown in Figure 9. The inclination of this segment at the instant of heel strike was found to be significantly less for the asphalt surface \((p < .03)\) than for the other surface conditions, \(F(3, 24) = 3.6\). No intercondition differences were found for the total range of motion.

The angle of the ankle joint during the stance phase for each of the surface conditions is shown in Figure 10. At the instant of heel strike the ankle joint was more plantar-flexed for the asphalt condition than for the other surface conditions, \(F(3, 24) = 4.4\). The range of motion from maximum dorsi-flexion to maximum plantar flexion was found to be greater for the rubberized asphalt and cinder surfaces than for the grass and asphalt surfaces, \(F(3, 24) = 4.6\). The relationship between the motion of the leg and first foot segment for each surface condition is shown in Figure 11. It would appear as though during the initial portion of the stance phase both segments contribute to the motion at the ankle joint. This is followed by a relatively greater contribution from the leg segment, then an almost immobile state for both segments. The final portion of the stance phase ankle joint motion is predominantly attributable to the
Fig. 9--Angle of the First Right Foot Segment During the Stance Phase
ANGLE OF THE RIGHT ANKLE JOINT DURING THE STANCE PHASE

Solid = Asphalt
Solid-Diamond = Grass
Dashed = Cinder
Dashed-Plus = Rubberized asphalt

Fig. 10--Angle of the Right Ankle Joint During the Stance Phase
Fig. 11--Angle of the First Right Foot Segment and the Leg
motion of the first foot segment. The significant differences in the ankle joint motion for each surface condition can be attributed to differences in the motion of the first foot segment at the instant of heel strike and to differences in the motion of the leg segment at the instant of toe-off.

The angle of the second foot segment for each of the surface conditions is shown in Figure 12. Each of the curves is characterized by initial segment motion, then immobility and finally additional motion. The onset of segment immobility was found to occur significantly later for the grass surface than for both the asphalt and rubberized asphalt surfaces, $F(3,24) = 4.7$. The recommencement of motion for both the rubberized asphalt and cinder surfaces was found to occur later for the rubberized asphalt surface than for the grass surface, $F(3,24) = 5.7$. The duration of segment immobility was greater for the rubberized asphalt surface than for both the asphalt and grass surfaces.

The relative motion of each of the foot segments for each surface condition is shown in Figure 13. It would appear as though the motion of the inter-segment joint was due to motion of both of the segments during the initial and final portions of the stance phase. The intermediary portion of the joint motion is characterized by relative segment immobility followed by a predominant motion of the first foot segment.
Fig. 12--Angle of the Second Right Foot Segment During the Stance Phase
Fig. 13—Angles of the First and Second Right Foot Segments
The angle of pronation for each of the surface conditions is shown in Figure 14. All of the curves show similarity in form. No significant inter-surface differences were found for any of the selected dependent variables.
ANGLE OF PRONATION OF THE RIGHT FOOT DURING THE STANCE PHASE

Fig. 14--Angle of Pronation of the Right Foot During the Stance Phase
CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Introduction

The purpose of this study was to examine the effects of various running surfaces on rearfoot stability, range of lower limb joint motion, and encountered pressures at selected locations on the plantar surface of the foot during running performances.

Review of Literature

Recent increases in the popularity of recreation running have also resulted in an increase in the number of lower limb injuries (Brody, Konecke, Day, & Kryder, 1981; James, Bates, & Osternig, 1978; Klein, 1979). Although a number of anatomic factors must be considered in the diagnosis and evaluation of running-related problems, there exists the contention that many of these problems are either directly or indirectly related to foot structure and function during the stance phase of the activity (James et al., 1978; Klein, 1979). In terms of foot functioning it would seem reasonable to suggest that this factor is, in turn, affected by the gait of the runner, the adopted footwear, and the terrain over which the runner moves.
Over recent years considerable attention has been directed towards understanding the biomechanical principles governing running performances (Cavanagh, Pollock, & Landa, 1977; Dillman, 1971; Fenn, 1930; James & Brubaker, 1973). Investigations by Bates, James, and Osternig (1978), Jansen and Jansen (1978), Nigg, Eberle, Frey, Luett, Segesser, and Weber (1978), Payne (1976), Plagenhoef (1980), and Scranton and McMaster (1976) have shown that the gait of a runner, and in particular the speed of ambulation, changes both the location and magnitude of the experienced foot contact forces and the range of subtalar joint motion. A concern for the effects of shoe type on foot functioning has resulted in evaluations of available footwear and statements about desirable shoe characteristics (Bates, James, Osternig, & Sawhill, 1978, 1980; Ellis, 1979; Nigg et al., 1978; Plagenhoef, 1980).

Research on the characteristics of the most "efficient" surface for a given sport has provided some indirect evidence for terrain effects on encountered foot contact forces and the forces transmitted to the leg and lower-limb motion control during running (Denoth & Nigg, 1981; Ellis, 1979; McMahon & Greene, 1973; Unold, 1973 [as cited in Nigg and Denoth, 1979]) and running-related sports (Bonstigl et al., 1975; Bowers & Martin, 1978). However, in none of these studies was attention directed towards specifically examining the effects of terrain on rearfoot stability, range of lower limb
joint motion, and encountered pressures at selected locations on the plantar surface of the foot.

Procedures

Nine female subjects were used in the study. Each subject performed five running trials for each of the four surface conditions. The surface conditions examined were: asphalt, grass, cinder, and rubberized asphalt. Each trial by each subject was recorded on film. The motion of the right lower limb when it was in contact with the target area was recorded. The film data was used to obtain the angle of foot pronation, the angle of inclination of the first and second foot segments, the leg angle, and angles of the ankle joint. All of the above parameters for each trial were "smoothed" using cubic spline curve fitting techniques and instantaneous values extracted. All of the angular parameters were averaged by surface condition. Pressures on the plantar surface of the right foot at the tuber-calcanei and the second metatarsal-phalangeal joint were directly recorded.

The pressure records for each trial were "smoothed" and normalized by dividing by subject body mass. The temporal characteristics of each trial relative to the instant of heel strike, maximum pressures, mean pressures, and the algebraic pressure impulses were computed and recorded for subsequent statistical analyses. A statistical analysis (p < .01), utilizing repeated measures analysis of variance procedures was conducted to ascertain if differences existed
between the surfaces, with the instantaneous temporal, kinematic, and kinetic characteristics of the right foot stance phase entered as dependent variables.

Results

For all surface conditions, the pressures in the region of the second metatarsal-phalangeal joint were consistently greater than those experienced in the heel region. The onset of pressure in the region of the second metatarsal-phalangeal joint occurred later than the onset of pressures in the heel region. The duration of the recorded pressures was generally greater for the second metatarsal-phalangeal joint region than for the heel region.

No significant differences were found among the surface conditions for the maximum pressures, time to maximum pressures, and mean pressures. The algebraic pressure impulses experienced in the heel region for the cinder surface were found to be less than those for both the asphalt and grass surfaces. It would appear as though these differences result from differences in both the duration and magnitude of the experienced pressures. The algebraic pressure impulses experienced in the region of the second metatarsal-phalangeal joint for the asphalt surface were found to be significantly less than those for both the rubberized asphalt and cinder surfaces. These results can be accounted for by significant and complementary findings for the pressure duration.
The asphalt surface stance phase duration was found to be significantly less than those for the other surfaces. For both the rubberized asphalt and cinder surfaces the leg was less inclined at the instant of toe-off than it was for the other two surfaces. The total range of motion during the stance phase was found to be significantly greater for the grass condition than for both the rubberized asphalt and cinder surfaces. The inclination of the first foot segment at the instant of heel strike was found to be significantly less for the asphalt surface than for the other surface conditions. No intercondition differences were found for the total range of motion. At the instant of heel strike the ankle joint was more plantar-flexed for the asphalt surface than for the other surfaces. The range of motion from maximum dorsiflexion to maximum plantar flexion was found to be greater for the rubberized asphalt and cinder surfaces than for the grass and asphalt surfaces. During the initial portion of the stance phase both the leg and first foot segments contributed to the motion at the ankle joint. This was followed by a relatively greater contribution from the leg segment, then an almost immobile state for both segments. The final portion of the stance phase ankle joint motion was predominantly attributable to the motion of the first foot segment. For all conditions the motion of the second foot segment was characterized by some initial movement, then immobility and finally additional movement. The onset of
segment immobility was found to occur later for the grass surface than for both the asphalt and rubberized asphalt surfaces. The recommencement of motion for both the rubberized asphalt and cinder surfaces was found to occur later than the asphalt surface. In addition, this event occurred later for the rubberized asphalt surface than for the grass surface. The duration of segment immobility was greater for the rubberized asphalt surface than for both the asphalt and grass surfaces. It would appear as though the motion of the first foot and second foot inter-segment joint was due to motion of both of the segments during the initial and final portions of the stance phase. The intermediary portion of the joint motion was characterized by relative segment immobility followed by a predominant motion of the first foot segment. No significant inter-surface differences were found for the angle of pronation.

Discussion

The relative timing and magnitudes of the representative pressures in the heel and metatarsal-phalangeal joint regions support the findings of Bates et al. (1981) and Scranton and McMaster (1976). That is, during running performances for so-called "heel-toe runners" pressures are initially experienced on the surface of the heel. Shortly into the stance phase the center of pressure moves to the forefront region where it stays for the majority of the remainder of the stance phase.
The results of the study provide some indication of surface-related gait changes. There is no evidence to suggest surface-related changes in experienced foot contact pressures. This is not supportive of the results of Unold (1973) as reported by Nigg and Denoth (1979), although their measurement was of foot-ground impact rather than of foot-shoe forces. There exists the possibility that the surfaces examined in the present study had similar physical characteristics. Surface-related differences in the algebraic pressure impulses experienced in the region of the second metatarsalphalangeal joint can be accounted for by differences in the duration of the stance phase and time of second foot segment immobility. Both the asphalt and grass surfaces yielded the shortest stance phases which were accompanied by the shortest relative times of forefoot immobility. This finding is in contradiction to the findings of Scranton and McMaster (1976) who found that speed of gait increases are accompanied by relative increases in the amount of time during which the center of pressure is located in the forefoot region. Differences in the size of the measurement area and technique between studies may account for this in part.

It would appear as though there exists no surface-related effects on forefoot stability or the intrinsic shock absorption capability associated with pronation. For both the asphalt and grass surfaces it would seem as though lower-limb motion is accomplished more by movement of the more proximal
segments although without measurements of the motion of the thigh, definitive statements cannot be made. However, previous research on speed-related gait changes would support this contention (Saito, Hoshikawa, Miyashita, & Matusui, 1972). This also provides some contradiction to the initial findings of McMahon and Greene (1979) who stated that surfaces of intermediate compliances probably produce the shortest stance phases. Measurements involving the entire surface of the foot may provide more data to explain differences.

Conclusions

The results of this study would appear to warrant the following conclusions.

1. Different surfaces affect the durations of portions of the stance phase.
2. Different surfaces do not affect the magnitude of the pressures experienced on the plantar surface of the skin overlying the heel and second metatarsal-phalangeal joint.
3. Different surfaces do not affect the intrinsic shock absorption capability associated with pronation.
4. Surface-affected changes in the lower limb segments are related to changes in the temporal characteristics of the stance phase.
Recommendations

Based on the results of this study the following recommendations are made for future studies.

1. A replication of the present study but using more diverse surfaces and instrumentation capable of measuring pressure changes over the entire plantar surface of the foot.

2. An examination of the interactions between shoe type and running surfaces.
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APPENDICES
APPENDIX A
USE OF HUMAN SUBJECTS
INFORMED CONSENT

NAME OF SUBJECT:

1. I hereby give consent to Dr. Donald R. McIntyre to perform or supervise the following investigational procedure or treatment:
   1) Record running performances using high-speed cinematographical techniques;
   2) Take direct measurements of the pressures experienced on two defined areas of the dorsum of the right foot.

2. I have (seen, heard) a clear explanation and understand the nature and purpose of the procedure or treatment; possible appropriate alternative procedures that would be advantageous to me (him, her); and the attendant discomforts or risks involved and the possibility of complications which might arise. I have (seen, heard) a clear explanation and understand the benefits to be expected. I understand that the procedure or treatment to be performed is investigational and that I may withdraw my consent for my (his, her) status. With my understanding of this, having received this information and satisfactory answers to the questions I have asked, I voluntarily consent to the procedure or treatment designated in Paragraph 1 above.

________________________________________
DATE

SIGNED: ___________________________ Signed: ___________________________
Witness Subject

or

SIGNED: ___________________________ SIGNED: ___________________________
Witness Person Responsible

Relationship

Instructions to persons authorized to sign:
If the subject is not competent, the person responsible shall be the legal appointed guardian or legally authorized representative. If the subject is a minor under 18 years of age, the person responsible is the mother or father or legally appointed guardian. If the subject is unable to write his name, the following is legally acceptable: John H. (His X ark) Doe and Two (2) witnesses.
## APPENDIX B

SELECTED ANTHROPOMETRIC CHARACTERISTICS

OF THE SUBJECTS

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<thead>
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