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Running With Running Shoes Versus Barefoot Running: A Videographical Analysis

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RUNNING WITH RUNNING SHOES VERSUS BAREFOOT RUNNING: A VIDEOGRAPHICAL ANALYSIS.

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THESIS ACCEPTANCE

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ABSTRACT

The purpose of this study was to kinematically describe the movements of the lower extremities in running with running shoes and running barefoot. Another purpose of this study was to identify and compare the anatomical and mechanical adaptations that occur. Seven college age females, members of the University of Nebraska at Omaha cross-country team, and one local competitive long-distance female runner 27 yrs old, were subjects of this study. All subjects were free of any physical disability that could have caused an impaired performance.

All subjects completed one testing session consisting of three acceptable trials each with and without their running shoes. A trial was defined as acceptable when the speed of the subject was 3.8 $\pm$0.19 m/sec and a complete running stride was in the field of view of the camera. Videography (60 fields /sec) was used to film the subjects from the sagittal view. The data capture, digitizing, data calculations, and display were performed by using the Peak Performance Technology PEAK2D Software running on a Zenith 80386 computer. A SONY 1341 Trinitron monitor and a Panasonic AG 7300 video cassette recorder controlled by the Zenith computer, were used to digitize the videography data.

The results obtained from the analysis of the parameters used revealed significant differences between conditions for

the vertical heel velocities before and at touchdown, and the strut length at toe off. No significant differences between conditions were found for the remaining parameters measured.

From the results of this study the following conclusions were made. Removal of running shoes indicated that the human spring apparatus of the lower extremity tends to shorten at touchdown and during the support phase to diminish shock (due to a lack of cushioning). Additionally, running shoes helped the runners to exhibit sufficient forward thrust and drive in order to project their bodies more efficiently during the nonsupport phase. These changes in running mechanics could be attributed to the protection of some elements of the musculoskeletal system due to the two different loading conditions.

From the findings of this study several recommendations were made concerning further research. Futute studies should employ appropriate methods for a detailed determination of the internal forces. Neurophysiological or mathematical modeling could be used for such an analysis. A longitudinal study should be conducted for better evaluation of the effects of barefoot training on injuries and performance.

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Table of Contents

Abstract.................................. ii

Acknowledgement........................... iv

Table of Contents......................... v

List of Tables............................ vii

List of Figures........................... viii

Chapter page

1. INTRODUCTION............................ 1

2. THE PROBLEM............................. 8

   Purpose................................. 8

   Hypothesis.............................. 8

   Delimitations........................... 9

   Limitations............................. 9

   Definition of Terms..................... 10

   Significance of the Study............... 11

3. REVIEW OF LITERATURE.................... 13

   Biomechanics of Running................. 13

   Running Shoes vs Barefoot Running....... 15

   Methodology-Procedures.................. 22

4. METHODS................................. 26

   Subject Definition...................... 26

   Experimental Procedure.................. 26

   Instrumentation......................... 28

   Parameters.............................. 30

Statistical Treatment........................ 35

5. RESULTS.................................... 36

6. DISCUSSION................................. 41

7. SUMMARY, CONCLUSIONS,

AND RECOMMENDATIONS........................ 46

Summary.................................... 46

Conclusions................................ 47

Recommendations............................ 48

REFERENCES..................................... 49

Appendix A..................................... 54

Appendix B..................................... 57

Appendix C..................................... 62

List of Tables

Table page

I. External vertical impact forces (ground reaction) in various types of movements and footwear........................ 19

II. Rearfoot movement studies conducted by various researchers........................... 20

III. Coefficients for predicting change in gastrocnemius length (in percent segment length) from joint (in degrees)......... 25

IV. Basic descriptive characteristics of each subject................................ 37

V. Group Means, Standard deviations, and dependent t-test values for each selected parameter.............................. 38

List of Figures

Figure page

1. Estimated number of joggers in the United States.................................... 1
2. Effet of cushioning on peak impact force during jump landings........................ 4
3. The gait cycle in running........................ 7
4. Hip, knee, and ankle as function of time......... 14
5. Comparisons of knee flexion-extension, ankle plantarflexion-dorsiflexion between jog and run, with superimposed electromyography analysis...... 16
6. Runway plan of the Gait Analysis Laboratory at UNO................................ 27
7. Angles used for the calculations of the ankle angle............................. 33
8. Conventions used for the ankle, knee, and hip angles.................................. 34
9. Vertical displacement of the center of the mass for all the subjects for running with running shoes over the running cycle..................... 55
10. Vertical displacement of the center of the mass for all subjects for barefoot running over the running cycle.............................. 56
11. Illustration of the differences in ankle angle means at touchdown, midsupport, and toe off,

for barefoot running and for running with running shoes.................................... 58

12. Illustration of the differences in knee angle means at touchdown, midsupport, and toe off, for barefoot running and for running with running shoes.................................... 59

13. Illustration of the differences in strut length means at touchdown, midsupport, and toe off, for barefoot running and for running with running shoes.................................... 60

14. Illustration of the differences in gastrocnemius length means at touchdown, midsupport, and toe off, for barefoot running and for running with running shoes.................... 61

15. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes Subject 1... 63

16. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes Subject 2... 64

17. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes

Subject 3 65

18. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes Subject 4 66

19. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes Subject 5 67

20. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes Subject 6 68

21. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes Subject 7 69

22. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes Subject 8 70

INTRODUCTION

The realizatation of the beneficial effects of exercise has resulted in a fitness movement throughout the world. Sport has become increasingly important in the lives of many individuals. Running has become a very pleasant daily routine for many. It has been estimated that the number of joggers in the USA has reached 30 million, which is more than 10% of the total population (Cavanagh, 1980; Krissoff & Ferris, 1979). See figure 1.

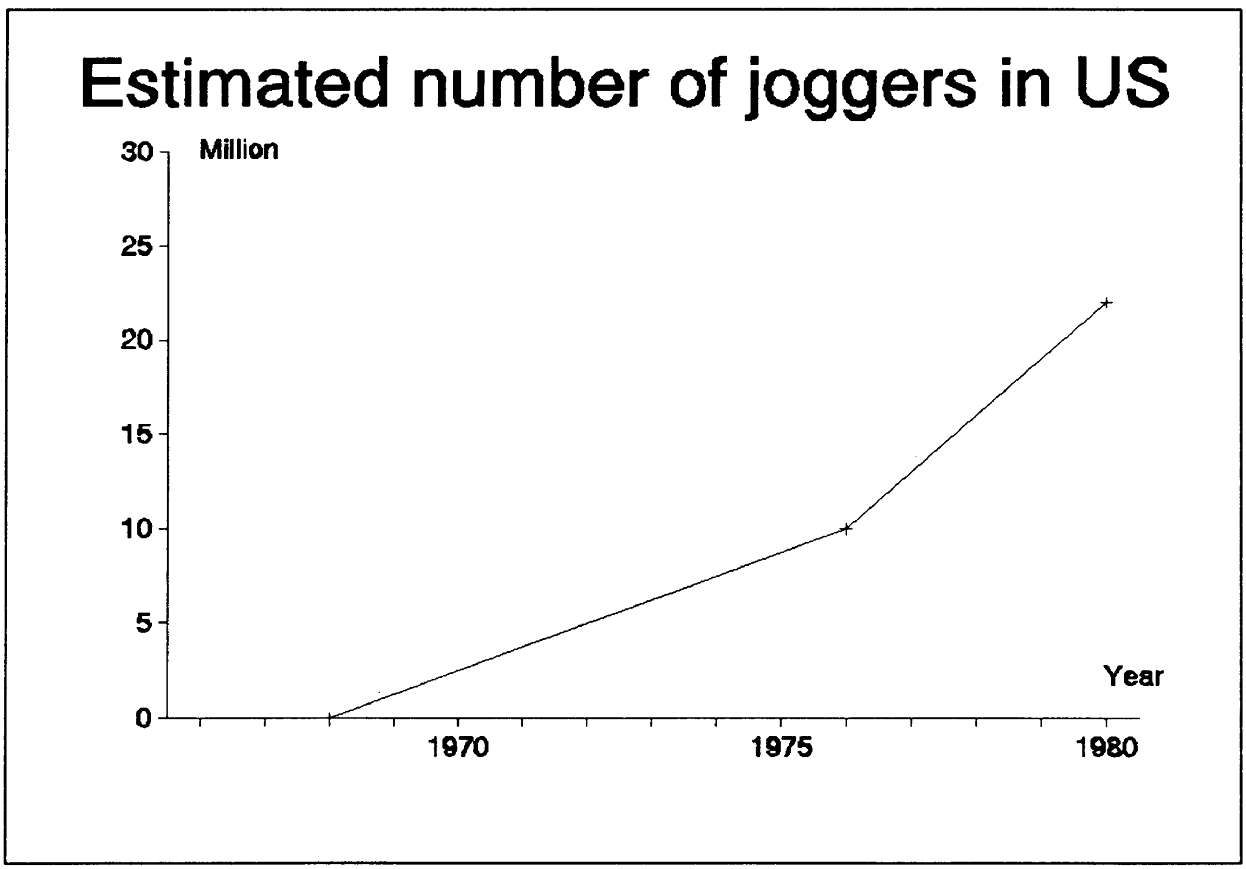

Figure 1. Estimated number of joggers in the United States (Krissoff & Ferris, 1979, 1).

This large increase in running population significantly affected the area of equipment technology. The newest running shoe models are completely different than the running shoe 20 years ago. Now, the shoe affects the athlete's performance and serves to support the foot as a tool, as a shock absorber, and as a launching pad.

Although most runners wear running shoes, we should still ask if the shoes are necessary. The examples of athletes like Zola Budd, Bruce Tulloh and Abebe Bikila show us that perhaps running performance can be very high without shoes. In 1975 Ariel said, "At the present time, there are no athletic shoes available which consider the 'athlete in the shoe'. In fact, some of the shoes may contribute to injury. Some of the best running apparatus used in past, and still available, belongs to the marathon runner from Ethiopia who ran barefooted in the 1960 and 1964 Olympic games and won the gold medal."

In 1987, Robbins and Hanna disputed the value of running shoes. They asserted that the rigid system of footwear between the foot and the surface didn't allow the human foot to react properly during impact. They indicated barefoot runners in international competitions do not display frequent injury while demonstrating very good performances. Reports about barefoot populations in underdeveloped countries indicate a rarity in lower extremity injury. Robbins & Hanna also reported that a West-Germany physical education instructor trained hundreds of barefoot people in sports involving running and jumping over a period of many years. He did not mention a single impact-related lower extremity injury in this population. Reports from countries, such as Haiti, where both barefoot and shoe population co-exist, indicate high rates of lower extremity injury only in the shoe population (Robbins & Hanna, 1987).

On the other hand, research by Radin, Orr, Kelman, Paul, and Rose, (1982) and Voloshin & Work, (1982) has shown, that a lack of sufficient shock attenuation is linked to degenerative changes in joints and low back pain. Therefore, repeated loading of a magnitude of two or three times body weight (BW) might produce negative biologic effects if it is not attenuated. As a result, a logical performance characteristic of a running shoe would be to attenuate or delay the application rate of impact forces and thus help to prevent the body's own natural shock absorbers from being overloaded (Clarke, Frederick, Cooper, 1983; Nigg, 1986). Additionally, when compared to barefeet, running shoes have shown better results in reducing peak impact force while running (Clarke et al, 1983; Nike Sport Research review, 1988). See figure 2.

Additionally, other researchers have shown differences between barefoot and shoe conditions. The injury rate among aerobic dancers wearing shoes is lower than that of barefoot dancers (Richie, Kelso, Bellucci, 1985). Rearfoot kinematic

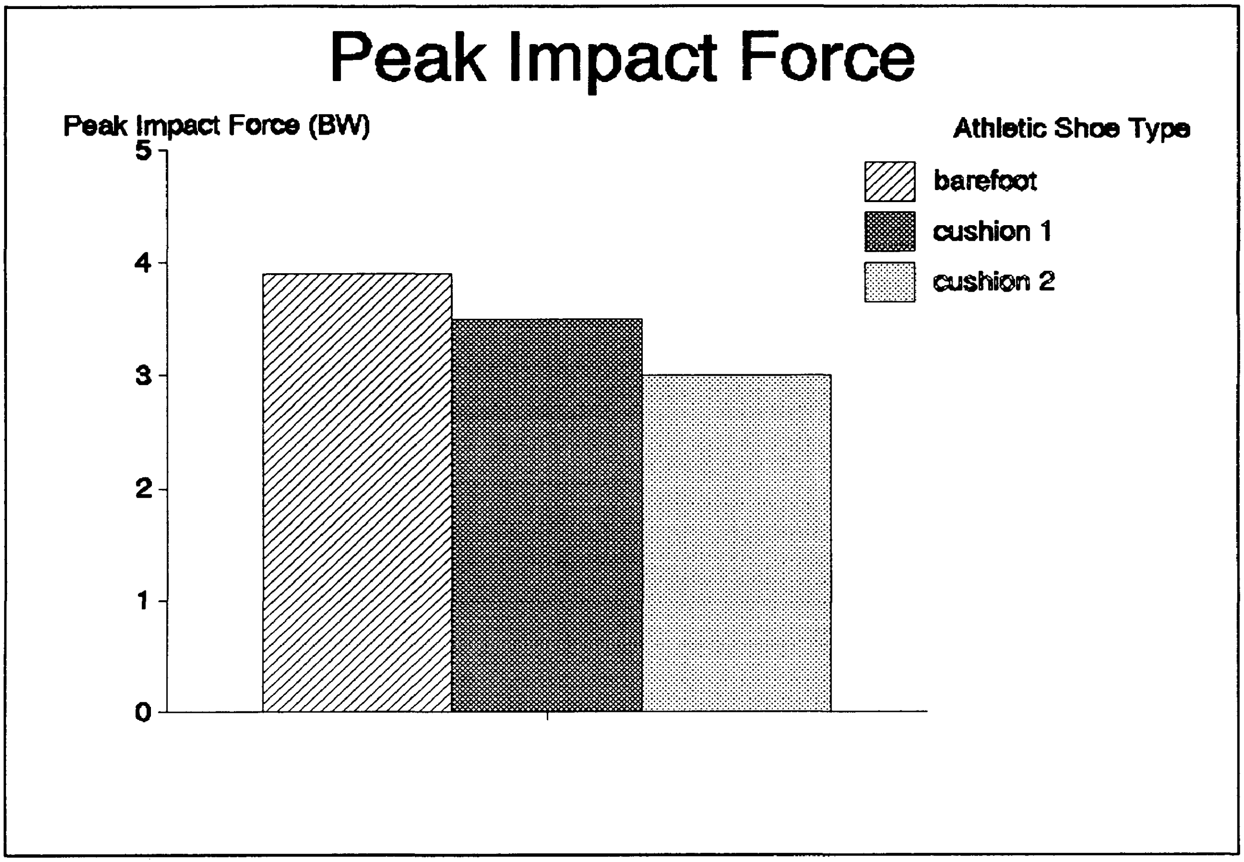

Figure 2. Effect of cushioning on peak impact force during jump landings (Nike Sport Research Review, 1988, 3).

variables are significantly different when comparing barefoot running to running with running shoes (Clarke, Frederick, Hamill, 1984). Oxygen cost of barefoot running was found to be similar to the cost for running with EVA (ethynyl vinyl acetate) shoes (Frederick, Clarke, Larsen, Cooper, 1983). This is surprising when you consider that the shoes used in this study weighed just under 290 g per shoe.

Additional kinematic changes have been observed in the sagittal view (mainly knee flexion velocities) when barefoot running was compared to running with running shoes (Clarke et al, 1983; Bates, Osternig, Mason, James, 1978).

Regardless of the condition of running, (with or without shoes) a consistent description of the gait cycle will be used throughout this paper. The gait cycle is divided into two periods: the stance phase (weightbearing or support period) and the swing phase (non-support period). During the normal walking cycle, the stance phase encompasses approximately 60% of the cycle while the swing phase makes up the remaining 40%. The gait cycle starts with heel strike on a single foot, and ends with heel strike on the same side. Stride length is a measure of the length of this single gait cycle. The stance phase is divided into heel strike, foot flat, heel rise, and toe off. The swing phase is divided into acceleration, toe clearance, and deceleration phases.

The average walker progresses at approximately 120 steps per minute, or a gait cycle time of approximately 1 second from heel strike to heel strike (Hutton, Scott, Stokes, 1976; Mann, 1982). As the speed of gait increases, the period of foot support diminishes and the period of swing increases. A runner progressing at a 5 min per mile pace decreases his cycle time to 0.6 sec. The stance phase, in this case, diminishes from 0.6 sec in walking to 0.2 sec in running. As a percentage of the gait cycle, the stance phase decreases to 33% of the cycle. During walking there is always a period in which one or both feet maintain contact with the ground.

Double limb support occurs through the first and the last 12% of the stance phase. The double support phase is lost during running. As gait speed increases, a float phase develops in which both feet are off the ground simultaneously (Bateman & Trott, 1980).

The gait cycle during the act of running has also been described (James & Brubaker, 1973; Slocum & James, 1958). The stance phase is divided into three separate periods: foot contact (the point of initial ground contact), mid-support (the period of full-weight acceptance, until ankle plantar flexion begins), and toe off. Swing phase is also divided into three periods: follow through (or the time from toe off until maximum hip extension), forward swing (the period of flexion of the hip, until maximum hip flexion), and foot descent (See Figure 3).

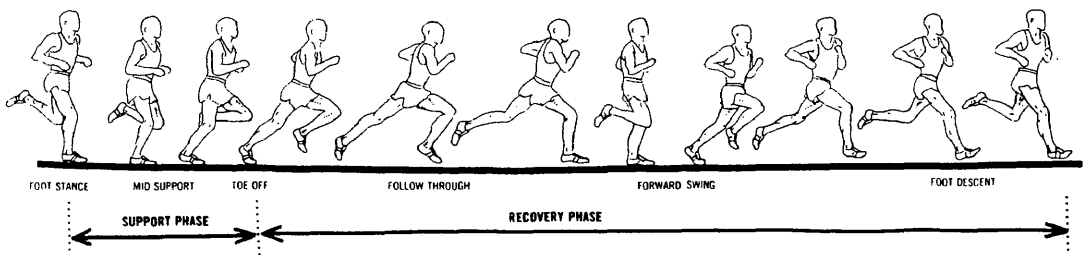

Figure 3. The gait cycle in running (Slocum & James, 1958, 101).

THE PROBLEM

PURPOSE

The purposes of this study were to:

1) Kinematically describe the movements of the lower extremities in running with running shoes and barefoot.

2) Identify and compare the anatomical and mechanical adaptations which occur at the lower extremities in barefoot running and running with running shoes.

HYPOTHESIS

There were no significant difference at the .01 level in the following parameters, between running with running shoes and barefoot.

a) Stride length.

b) Support and non-support times.

c) Vertical oscillation of the COM.

d) Maximum right knee flexion velocity after touchdown.

e) Maximum right hip flexion velocity after toe off.

f) Vertical and horizontal velocity of the right heel before and at the moment of touchdown.

g) Right tip toe velocity between heel strike and tip toe ground contact.

h) Strut lenqth at heel strike, mid-support and toe-off.

i) Gastrocnemius length at heel strike, mid-support and toe off.

j) Right ankle, knee, and hip angles at heel strike, mid-support and toe off.

DELIMITATIONS

Eight healthy female volunteers, seven from the University of Nebraska at Omaha cross-country team and one local competitive runner, were used as subjects. Each subject performed as many trials as necessary, to achieve six trials in which a complete running stride (right heel strike to right heel strike) was in the field of view and their speed was 3.8 $\pm$.19 m/sec. Three trials were performed with running with running shoes and three trials running barefooted. All trials were videotaped by one camera operating from the sagittal view.

LIMITATIONS

The results may be affected by the running speed that the subjects used during the testing session. In order, to reduce the amount of bias, the running speed was controlled.

A trial was considered usable, only when the subject ran at 3.8 $\pm$.19 m/sec (3.99 - 3.61 m/sec range), (7 min per mile pace). A metronome was operating at that rate to help the subjects maintain the desired speed. Photocells and a timer were placed along the runway to measure the subjects speed continuously.

Another aspect that could have been controlled was the type of running shoes worn by the subjects. The type of shoes were not controlled in order to make the runners feel most comfortable while running.

DEFINITION OF TERMS

Ankle angle - The anterior angle formed by the lines that connect the tip of the toe with the heel, and the lateral malleolus with the lateral joint axis of the knee. The intersection of these lines is the vertex of the angle.

Center of the mass - The point at which the entire weight of a body may be considered concentrated so that if supported at this point the body would remain in equilibrium in any position.

Follow through period - The time from toe-off until maximum hip extension.

Forward swing - The elapsed time of flexion of the hip, until maximum hip flexion.

Foot contact (moment of touchdown) - The instant of initial ground contact of any part of the foot.

Hip angle - The anterior angle formed by a vertical line and the line which connects the greater trochanter of the hip with the lateral joint axis of the knee. The intersection of these lines is the vertex of the angle.

Knee angle - The posterior angle formed by the lines that connect the lateral malleolus with the lateral joint axis of the knee, and the greater trochanter of the hip with the lateral joint axis of the knee. The lateral joint axis of the knee is the vertex of the angle.

Mid-support - The instant when the tibia is perpendicular to the ground.

Non-support time - The swing phase time.

Stance phase time - Time from foot contact with the ground until toe-off.

Stride length - The distance between two consecutive right heel strikes.

Strut length - The distance between the hip and the fifth metatarsal head.

Support time - The stance phase time.

Swing phase time - Time from toe-off to the next foot contact.

Toe-off - The instant at which the foot leaves the ground.

Vertical oscillation of the COM - The difference between the maximum and the minimum vertical distance of the COM from the ground.

SIGNIFICANCE OF THE STUDY

The results of the study provided a comparison between the anatomical and the mechanical adaptations of running barefoot and running with running shoes. This study is adding more information to the literature on the reaction of the human body to running with or without running shoes.

This information could be useful to coaches who are considering some barefoot training and to podiatrists and the sport-shoes companies, who are now trying to give more mobility and freedom to the foot (example, Adidas Torsion shoes).

REVIEW OF LITERATURE

The present review of literature has been divided in three parts. The biomechanics of running (certain anatomical and mechanical characteristics which are held in common, regardless of differences in individual style), the arguments and the available findings for running with running shoes vs barefoot running, and finally the literature about the methodology and procedures used.

Biomechanics of Running

The gait cycle has been described during the act of running (James & Brubaker, 1973; Slocum & James, 1958). The description indicated two basic phases: the stance phase and the swing phase. The stance phase, or support phase, is divided into three separate periods: foot contact (the instant of initial ground contact), mid-support (the period of full-weight acceptance, until ankle plantar flexion begins), and toe off (the instant where the foot leaves the ground). Swing phase is also divided into three periods: follow through (or the time from toe off until maximum hip extension), forward swing (the period of flexion of the hip, until maximum hip flexion), and foot descent (the time from maximum hip flexion to the next foot contact) (See Figure 3).

In 1987, Cavanagh described in detail the angles found at the joints of the lower extremities as a function of time in the gait cycle (See Figure 4). As the foot strikes the ground

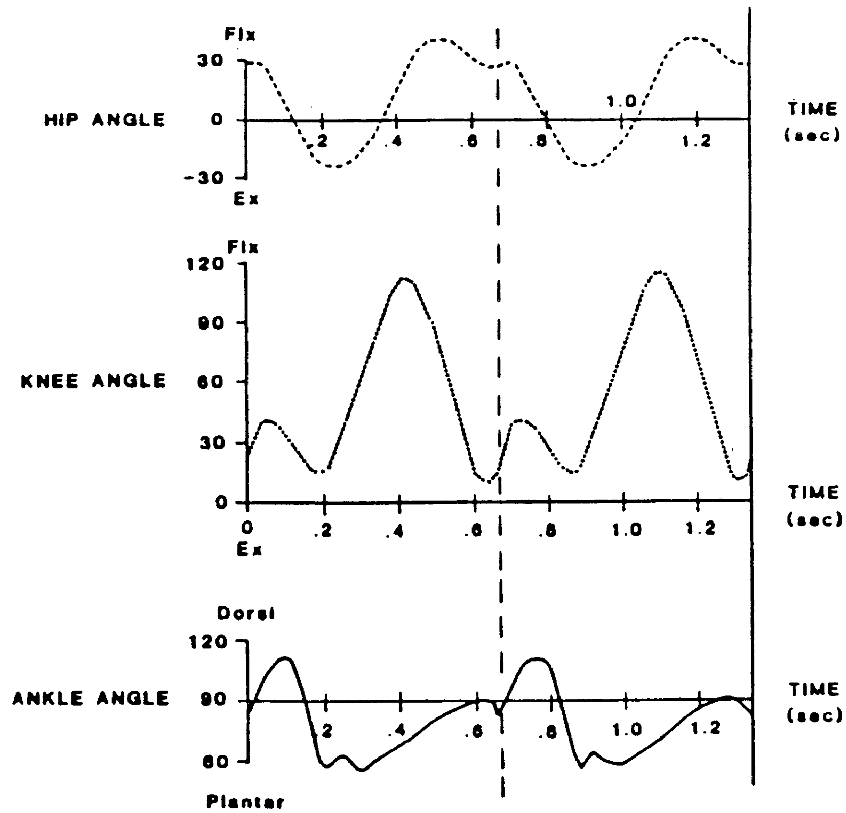

Figure 4. Hip, knee, and ankle angles as function of time (Cavanagh, 1987, 205).

dorsiflexion begins immediately. It is accompanied by knee flexion. The ankle is in plantarflexion before foot strike and rapidly changes to dorsiflexion at foot strike. The dorsiflexion continues as the knee flexes during the mid-support phase. Dorsiflexion continues after maximum knee flexion, but soon knee extension and hip extension take place. After toe off, the ankle angle varies only slightly during the first part of the swing phase, but is then gradually dorsiflexed through maximum knee flexion, maximum hip flexion, and only when the knee begins to extend in preparation for foot strike, does plantarflexion begin.

Mann and Hagy (1980) analyzed the gait cycle in walking, jogging and running using electromyography and cinematography techniques. In Figure 5 comparisons of knee flexion and extension, and ankle plantarflexion and dorsiflexion between jog and run were displayed with superimposed electromyography analysis.

Running shoes vs barefoot running

The history of the running shoe is both extensive and absorbing. According to Cavanagh (1980) the early man in America was a runner, and his shoe was found in a cave in Oregon. At the modern end of the continuum, the pedestrians of the late 19th century, the early Olympians, and the phenomenal growth of running in the 1970 were all factors which instigated today's development of the running shoe.

It is a commonly advertised belief, that the running shoe aids in running performance. However, the examples of athletes like Zola Budd, Bruce Tulloh and Abebe Bikila who run barefoot show us that perhaps running shoes don't really affect running performance. Bruch Talloh, a famous European runner, thought

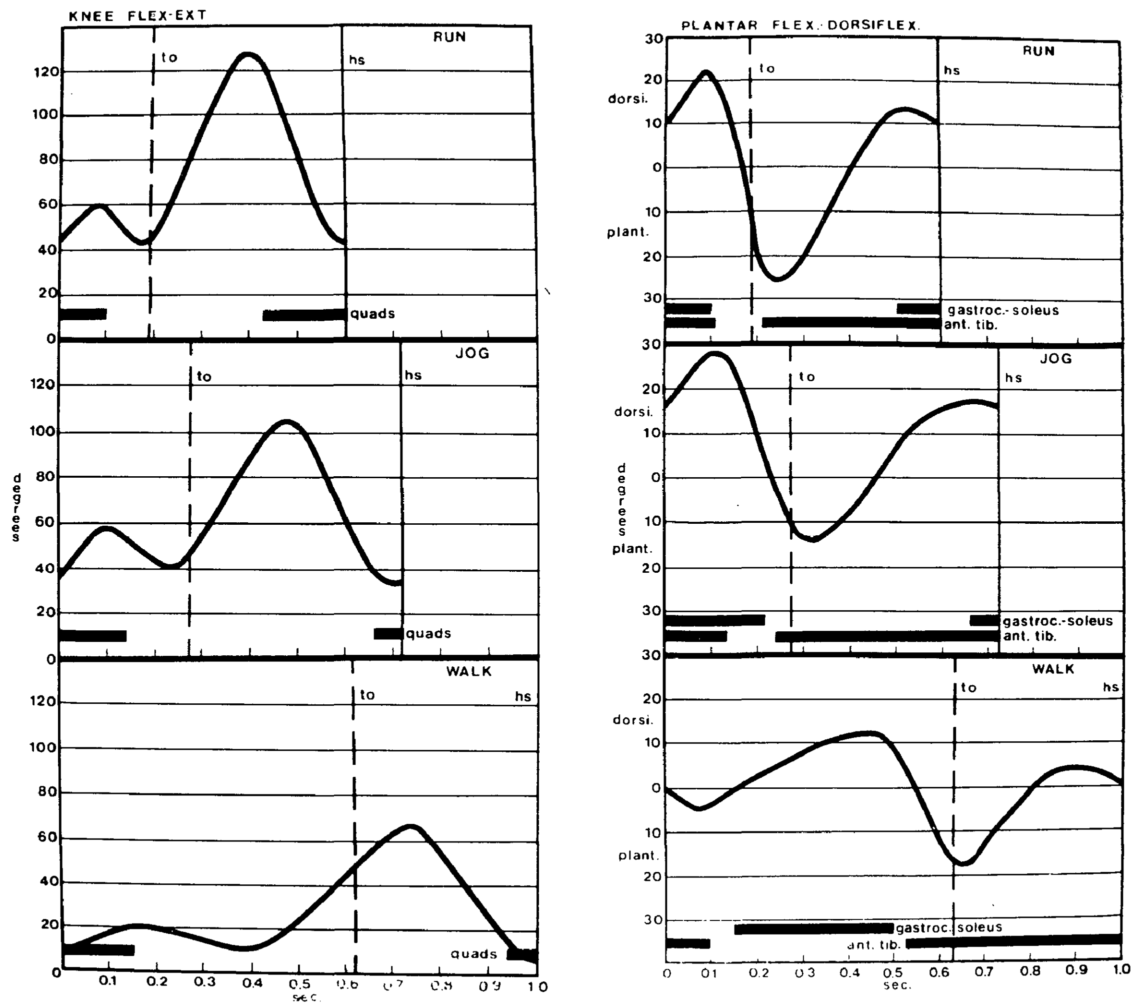

Figure 5. Comparisons of knee flexion-extension, and ankle plantarflexion-dorsiflexion between jog and run, with superimposed electromyography analysis (Mann & Hagy, 1980, 170-171).

that reducing the mass of the lower limbs would cause a reduction in energy expenditure and perhaps leave that small but significant margin available for faster times. Therefore, in 1958 he started running without shoes and experienced success. After that he did not wear shoes in a race unless the surface was too hostile for the foot.

In 1975, Ariel analyzed 35 different running shoes and found that human factors were not taken into consideration when designing these shoes. He suggested barefoot running as a possible alternative to running with running shoes. Robbins and Hanna published articles in 1987 & 1988 where they described the effect of loading on the medial longitudinal arch of the foot and the overload protection of the lower extremities. They found that the lack of a feedback control system, which would serve to moderate loading during locomotion, may be responsible for many injuries. The rigidity of athletic footwear does not let the feedback control system react properly. This can explain why there is an extremely low-running injury frequency in barefoot populations when compared to shod populations.

Contrary to the findings of Ariel (1975) and Robbins & Hanna (1987, 1988), Radin et al (1982) and Voloshin & Wosk (1982) provided evidence that impact forces can have injurious effects on the body. Subotnick (1985) indicated that the ground reaction force is between 2 and 5 body weight (BW) during running at various speeds. A logical performance characteristic of a running shoe is to attenuate these impact forces and help prevent the body's own natural shock absorbers from being overloaded.

Clarke et al (1983) measured lower values for the initial peak of the vertical force for running with shoes vs running barefoot. These results are also supported by a Nike Research Sport Review (1988). Richie et al (1985) has shown that the injury rate among aerobic dancers wearing shoes is lower than that of barefoot dancers (53.6% vs 64.9% injured). In addition, Table I presents the differences in external impact vertical forces (ground reaction) for running shoes and barefoot.

Luethi, Denoth, Kaelin, Stacoff, and Stuessi (1987) have found that while running barefoot the extrinsic muscles of the foot are able to stabilize the foot during impact and the internal structures that are mainly loaded are the soft tissue beneath the heel, the joints and the bones. In running with shoes the same muscles cannot "equalize the greater moments produced especially by harder shoe soles" (p. 934). As a result, initial joint motion is increased during impact.

Another area which is affected by the condition of running barefoot vs wearing running shoes is rearfoot movement. Bates et al (1978) and Nigg & Luethi (1980) have shown a tendency for barefoot runners to strike the ground in a less supinated position. In Bates' study removal of the shoe resulted in a statistically significant increase in the period of pronation as a percentage of the support phase. Nigg, Luethi, Stacoff, and Segesser (1981) have shown that the

Table I. External vertical impact forces (ground reaction) in various types of movements and footwear (Nigg, 1986, 21)

Movement	Velocity (m/s)	Footwear	Fmax (N)	Fmin (BW)	Author	Year
Walking heel-toe	1.3	barefoot	-	0.6	Cavanagh	81
Walking heel-toe	1.3	casual shoe	-	0.3	Cavanagh	81
Running heel-toe	2.7	run. shoe	-	2.8	Clarke	82
Running heel-toe	3.4	barefoot	1365	2.0	Frederick	81
Running heel-toe	3.8	barefoot	1590	2.3	Frederick	81
Running heel-toe	4.5	run. shoe	-	2.2	Cavanagh	81
Running heel-toe	4.5	barefoot	1963	2.9	Frederick	81
Running heel-toe	5.5	run. shoe	2350	3.6	Nigg	81

rearfoot angle at takeoff is close to neutral when running barefoot, and significantly more supinated when shoes are used. They also demonstrated that, running barefoot resulted in significantly less calcaneus movement in the first 10% of foot contact. In a review of literature Clarke (1984) presents all the available findings concerning rearfoot movement in running barefoot and with running shoes (See Table II).

The primary focus of the current study was the change of kinematic variables in the sagittal plane. When comparing

Table II. Rearfoot movement studies conducted by various researchers (Clarke, 1984, 178)

Study	Condition	Pace (m/s)	N	Parameters A	B	C	D
Bates(1978)	Barefoot	3.8-4.5	10	1.9	-8.6	95	10.5
Bates(1978)	Shoe	3.8-4.5	10	10.4	-7.2	82	17.6
Bates(1978)	Shoe	3.3	10	8.8	-6.8	99	15.6
Bates(1979)	Shoe	4.5	11		-9.1	72	
Bates(1980)	Shoe	4.1-4.9	2		-11.0	45	
Cavanagh(1978)	Shoe	4.5	4				16.5
Cavanagh(1978)	Shoe/orth	4.5	4				10.0
Clarke(1980)	Shoe	4.5	15	3.7	-10.8	45	14.5
Clarke(1983)	Shoe	3.8	8	5.7	-11.4	94	17.1
Clarke(1983)	Shoe/orth	3.8	8	6.9	-8.9	102	15.8
Clarke(1983)	Shoe	3.8	10	4.9	-11.7	94	16.6
Nigg(1980)	Barefoot	3.0	54	0.8			
Nigg(1980)	Shoe	3.0	45	7.5			

Parameter Key: A. Touchdown angle (deg) B. Maximum Pronation Angle (deg) C. Time to Maximum Pronation (msec) D. Total Rearfoot Movement (deg)

barefoot running vs running with running shoes Clarke et al (1983) found that in the barefoot condition the runners exhibited less hip flexion (26 deg to 27.8 deg), more knee flexion (23 deg to 21 deg) and a lower horizontal heel velocity at touchdown (0.56 m/sec to 1.3 m/sec). Significant differences were also found for the ankle angle at touchdown. Immediately after touchdown, there were also differences in the peak knee flexion velocity. According to Greene & McMahon (1979) and Clarke et al (1983) it was hypothesized that the reason for the differences in kinematic variables is adaptation of the leg in order to decrease the magnitude of the vertical force impact peak (VFIP). However, it is not clear in the study by Clarke et al (1983) if the results are from overground or from treadmill running (speed used 3.8 m/sec). Also, the focus of the study wasn't to examine the relationship of barefoot running versus running with running shoes, but rather to define biomechanical measurements of running shoe cushioning properties.

Bates et al (1978), in a three dimensional study of the lower extremity function during the support phase of running (treadmill running-speed used 3.8-4.47 m/sec), found differences between running with running shoes and barefoot running. At heel strike the runners exhibited more knee flexion (163.6 to 161.8 deg) and less dorsiflexion (115.8 to 124.8 deg). At toe off the knee angle was almost the same (173.4 to 173.6 deg) and the ankle was more plantarflexed (149.5 than 143.8 deg). The total support time was less in barefoot running (0.2041 sec) than in running with running shoes (0.2124 sec).

It is also very interesting that the oxygen cost of barefoot running was similar to the oxygen cost with shoes containing EVA (ethynil vinyl acetate) midsoles (Frederick et al, 1983). This is surprising when you consider that the shoes in this study weighed just under 290g per shoe. In barefoot running there is an increased energy cost of cushioning the body, because of the addition of another sprung element to the system. The plantar flexion of the foot at footstrike is a shock-absorbing strategy, but it brings with it an increase in the eccentric contraction of the anterior shank musculature which apparently raises oxygen cost.

Methodology-Procedures

In the present study the videography method was used in order to analyze the kinematic differences for barefoot running vs running with running shoes. The procedure used was described in Stuberg, Colerick, Blanke, and Bruce (1988). Stuberg et al compared a clinical gait analysis method using videography and temporal-distance measures with 16 mm cinematography. Cavanagh (1984) has described the proper placement of markers for kinematic analysis of distance running.

In a review of the biomechanics of running, Williams (1986) mentioned that speed affects the majority of the biomechanical parameters measured during running. In order to control speed, researchers have used various procedures. Running on a treadmill was used by Bates et al (1978) and Cavanagh (1987). However, as Williams mentioned, there are significant differences between treadmill and overground running. Clarke et al (1983) monitored the speed of running by photocells placed along the runway and a good trial was one in which the subject ran within 5% of 3.8 m/sec.

Lastly, the specific kinematic parameters, which should be evaluated in the qualitative analysis were indicated by Williams (1986), Cavanagh (1987) and Nigg (1986). Reported values of kinematic variables of interest to this study are presented below. All values were determined for overground running with running shoes.

a) Support and non-support times. Support time: Stance phase time. From foot contact until toe off. Non-support time: Swing phase time. As indicated by Cavanagh (1987), support phase could be 23 msec or 33% of the running cycle at 3.83 m/sec running speed.

b) Vertical oscillation of the center of the mass. Luthanen and Komi (1978) reported vertical oscillation of 10.9 cm for 3.9 m/sec running speed.

c) Joint and segment angles. Figure 4 describes the hip, knee, and ankle angles at 3.83 m/sec running speed, as presented by Cavanagh (1987). Williams (1986) used one more angle, the trunk angle. This angle is defined as the angle between the shoulder joint, the hip joint and the vertical (vertex at the hip joint).

e) Velocity changes within the running cycle. Heel velocity has been reported to be approximately 1.0 m/sec immediately before contact with the ground for 3.5 m/sec running speed (horizontal component 0.9 m/sec and vertical component 0.55 m/sec, Williams, 1986).

f) Strut length (SL). Strut length is a variable that is important to walking and running in robots. According to Cavanagh (1990) while running on a treadmill running at 3.8 m/sec, the minimum strut length was 0.70 m and the maximum strut length was 1.08 m. SL was shortened at a rate of approximately 2m/sec during the cushioning phase.

g) Gastrocnemius length (GL). Grieve, Pheasant, & Cavanagh (1978) determined a second degree polynomial regression equations that can predict the GL from the angular data of the knee and the ankle joints. (See Table III). The derivatives of the GL-time curves can provide useful information concerning the change of the GL through the running cycle.

In summary, the above review of literature presents the biomechanics of running (certain anatomical and mechanical characteristics which are held in common, regardless of differences in individual style). The arguments and the available findings for running with and without running shoes

Table III. Coefficients for predicting change in gastrocnemius length (in percent segment length) from joint angle (in degrees)[a] (Grieve et al, 1978, 256)

	A_o	A_1	A_2
Ankle (n)	-22.18468	+0.30141	-0.00061
knee (k)	6.46251	-0.07987	+0.00011

[a]Joint angles are defined in the parameters section. Equations are of the form: $dL_n = A_o + A_1(N) + A_2(N)^2$, where dL_n is the length change attributable to angle n.

Note: $dL = dL_n + dL_k$.

were discussed. Literature concerning the methodology and procedures were also presented.

METHODS

Subject Definition

The subjects of the study were eight females. Seven (18-22 yrs old) were members of the University of Nebraska at Omaha women's cross-country team, and one (27 yrs old) was a local highly competitive runner. Their normal training was minimized two days before testing. On the day of testing each subject reported no physical disability that could affect the subject's performance. Each subject provided informed consent, prior to the testing session, in accordance with the procedures required by the Institutional Review Board of the University of Nebraska.

Experimental Procedure

All subjects were weighed and had their height measured prior to the testing session. The order of testing (shoes or barefoot) was randomized to eliminate the effect of practice or fatigue on the results. A general body warm up was also provided. It consisted of five minutes of cycling using an Airdyne cycle, and specific stretching exercises for the lower extremities. The testing session consisted of 3 acceptable trials running barefoot and 3 acceptable trials running with running shoes. A trial was considered acceptable when the speed of the subject was 3.8 $\pm$.19 m/sec (3.61-3.99 m/sec) (7min per mile pace) and a complete running stride right heel strike to right heel strike was in the field of view. The

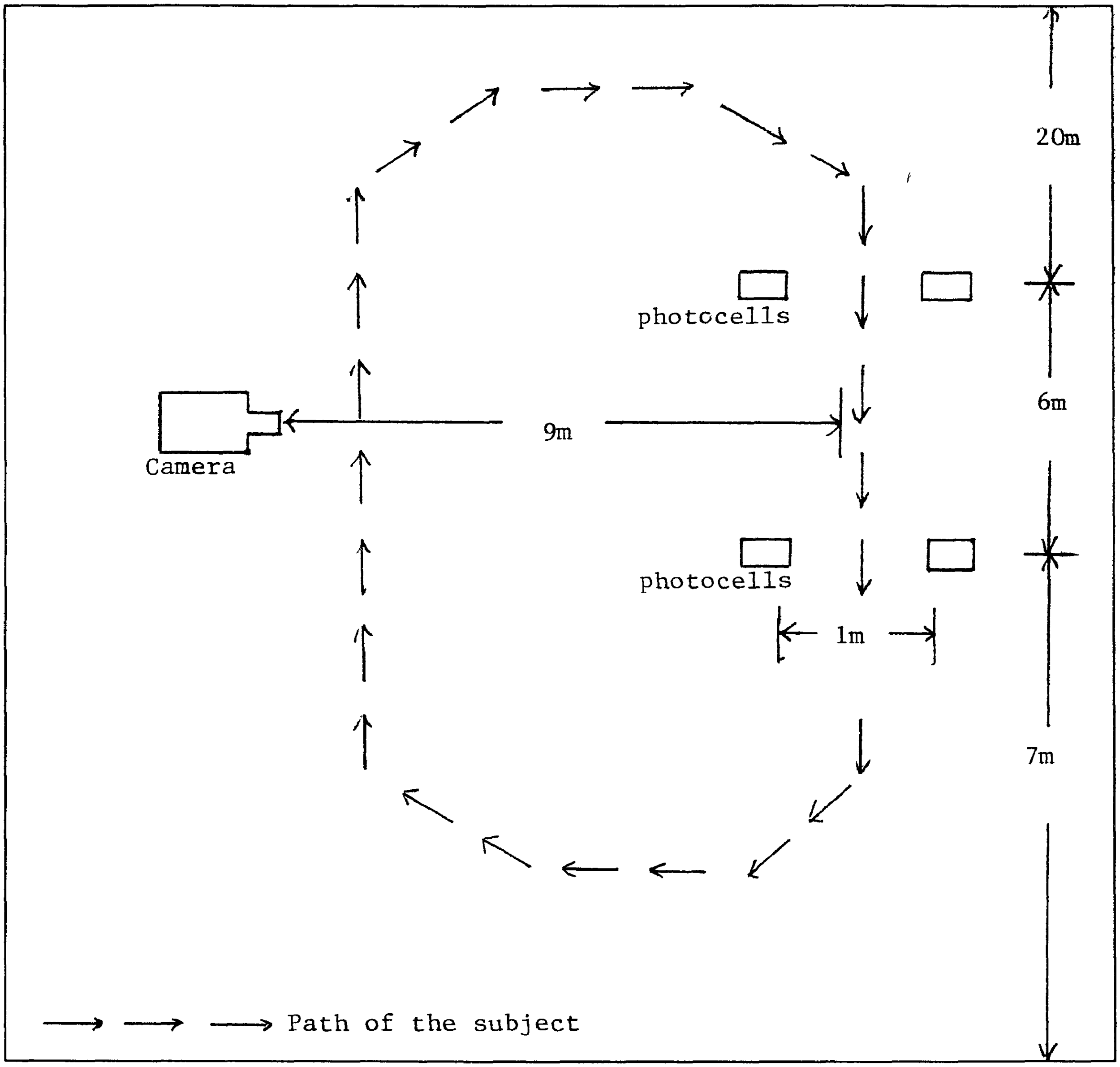

Figure 6. Runway plan of the Gait Analysis Laboratory at UNO.

speed of running was chosen as representative of a training pace for distance runners. To assist in maintaining a 3.8 m/sec pace, each subject ran continuously in a circle (See Figure 6). A metronome was used to determine foot strike at this pace, in order to help the subjects find the desirable running speed. Several practice trials were also provided. Each subject wore shorts and a sleeveless shirt. Markers were applied to identify the following landmarks:

1. right head of the fifth metatarsal
2. right heel underneath the calcaneus
3. right lateral and left medial malleolus
4. right lateral and left medial joint line of the knee
5. right lateral and left medial joint line of the elbow
6. right lateral and left medial joint line of the wrist
7. greater trochanter of the right hip
8. joint line of the right shoulder

Landmarks not marked but digitized:

1. tip of the foot bilaterally
2. tip of the longest finger bilaterally
3. heel bilaterally
4. left greater trochanter of the hip
5. joint line of the left shoulder
7. base of the neck
8. top of the head

All testing was performed at the University of Nebraska at Omaha Biomechanics Laboratory.

INSTRUMENTATION

Videography was used for the purpose of the study. A Panasonic AG 450 shuttered (SuperVHS) video camcorder, equipped with TV 8-80 mm 1:1.4 ZOOM lens, was positioned perpendicular to the center of the runway (See Figure 6). The camera was mounted on a tripod and leveled. The distance from the camera to the middle of the runway was 9 meters. The distance included in the field of view was 9.5 meters. The camera was set to operate at 60 fields/second with 1/1000 shutter. The distance leading to the runway was 20 meters. The distance from the runway to the wall was 7 meters.

A 1 meter horizontal reference scale was also included in the field of view. Fluorescent lighting of the laboratory was adequate for the purpose of this study. A metronome was operating during the testing session to help subjects adjust to the required speed (3.8 $\pm$.19 m/sec). The speed of running was monitored by photocells attached to a timer placed along the runway (See Figure 6).

The data capture, digitizing, data calculations, and display were performed using the PEAK Performance Technology PEAK2D Software running on a Zenith 80386 computer. A SONY 1341 Trinitron monitor and a Panasonic AG 7300 video cassette recorder controlled by the Zenith computer, were used to digitize the videography data.

The PEAK2D Motion Measurement System allows accurate manual digitizing from Super-VHS format video. The system imports a video image recorded on Super VHS videotape into the computer, where it is split into two pictures (fields), enhanced, and presented to the operator on the video monitor with a superimposed cursor. The cursor can be manipulated with an optical mouse to identify x,y coordinates. The researcher can then extract quantitative data on position and movement of the subject being studied.

PARAMETERS

The following parameters were measured:

Stride length was the distance between two consecutive right heel strikes. This parameter was calculated by the PEAK2D Software. The software subtracts the two horizontal coordinates of the right heel landmark. Distance was measured in centimeters.

Support time was the time between the right heel strike and the right toe off. This parameter was calculated by counting the number of frames which elapsed during the movement divided by the frame rate. Time was measured to the nearest hundredth of a second.

Non-support time was the time between the right toe off to the next right heel strike. This parameter was calculated by counting the number of frames which elapsed during the movement divided by the frame rate. Time was measured to the nearest hundredth of a second.

Center of Mass was determined by the PEAK2D Software. The software uses data available on weights and lengths of body segments to calculate the COM (Clauser, McConville, & Young, 1969; Hinrichs, 1990). COM was displayed as the x,y coordinates of the COM expressed in centimeters.

Vertical oscillation of the COM was defined as the difference between the maximum and the minimum vertical coordinates of the COM. This parameter was calculated directly from the PEAK2D Software. Oscillation was measured in centimeters.

Maximum right knee flexion velocity after touchdown was defined as the greatest (absolute value) angular velocity of the right knee angle during the support phase. This velocity was selected from the frame by frame knee angular velocities. Maximum knee flexion velocity was measured in degrees per second.

Maximum right hip flexion velocity after toe off was defined as the greatest (absolute value) angular velocity of the right hip angle during the non support phase. This parameter was selected from the frame by frame hip angular velocities. Maximum hip flexion velocity was measured in degrees per second.

Vertical and horizontal velocity of the right heel before and at the moment of touchdown. These velocities were determined by the PEAK2D Software from the right heel landmark. The software provides the right heel landmark's vertical and horizontal velocities frame by frame. The frames used were the frame before touchdown and the frame at touchdown. These parameters were measured in centimeters per second.

Right strut length at heel strike, mid-support and toe off. Right strut length was defined as the distance between the right hip landmark and the right fifth metatarsal head landmark. The frames of the heel strike, mid-support, and toe off were used for these measurements. All calculations were done by the PEAK2D Software. These parameters were measured in centimeters.

Right gastrocnemius length at heel strike, mid-support and toe-off. Gastrocnemius length was calculated from the right knee and the right ankle angles, at the heel strike frame, the mid-support frame and the toe-off frame using equations developed by Grieve et al (1978). These equations are of the form $dL_N = A_o + A_1(N) + A_2(N)^2$, where A_0, A_1, A_2 are coefficients relative to each angle, and where dL_N is the length change attributable to angle N. GL is equal to dL_N plus dL_K, where N is the right ankle angle and the K is the right knee angle (See Table III). A computer program created by the investigator was used for these calculations. The gastrocnemius length was measured in centimeters.

Right ankle angle at heel strike, at mid-support, and at toe off. Right ankle angle was defined as the angle formed by the lines that connect tip of foot with the heel underneath the calcaneus landmark, and lateral malleolus with the lateral joint line of the knee. Their intersection was the vertex.

PEAK2D software provided angles H and A frame by frame (Figure 7). The ASYSTANT Software was used for all the appropriate calculations in order to estimate the ankle angle desired frame by frame. The heel strike, midsupport, and toe off frames were used for these measurements. The angles were measured in degrees.

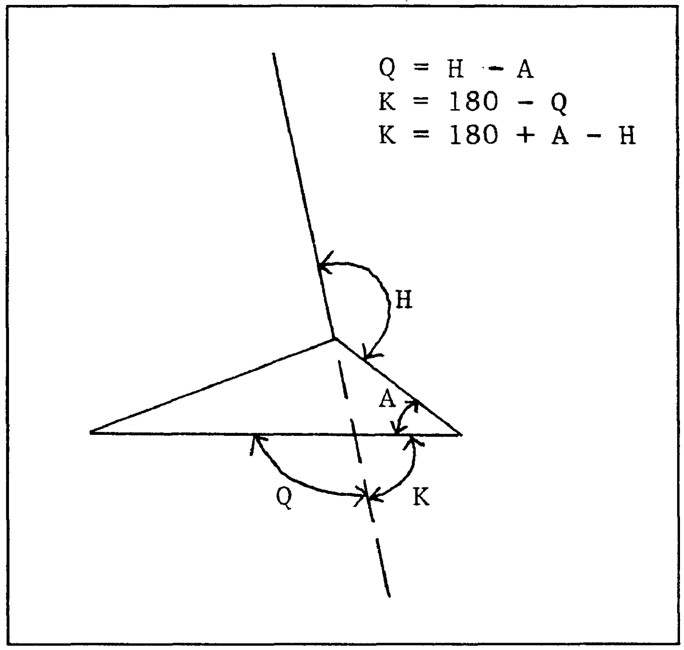

Figure 7. Angles used for the calculations of the ankle angle (K).

Right knee angle at heel strike, midsupport, and toe off. Right knee angle was defined as the angle formed by the lines that connect the lateral malleolus with the lateral joint line of the knee, and the greater trochanter of the hip with the lateral joint line of the knee. The lateral joint line of the knee was the vertex of the angle. PEAK2D Software provided us with the right knee angle frame by frame. The heel strike, midsupport, and the toe off frames were used for these measurements. These angles were measured in degrees.

Right hip angle at heel strike and at toe off. Right hip angle was defined as the angle formed by the vertical and the line which connects the greater trochanter of the hip with the

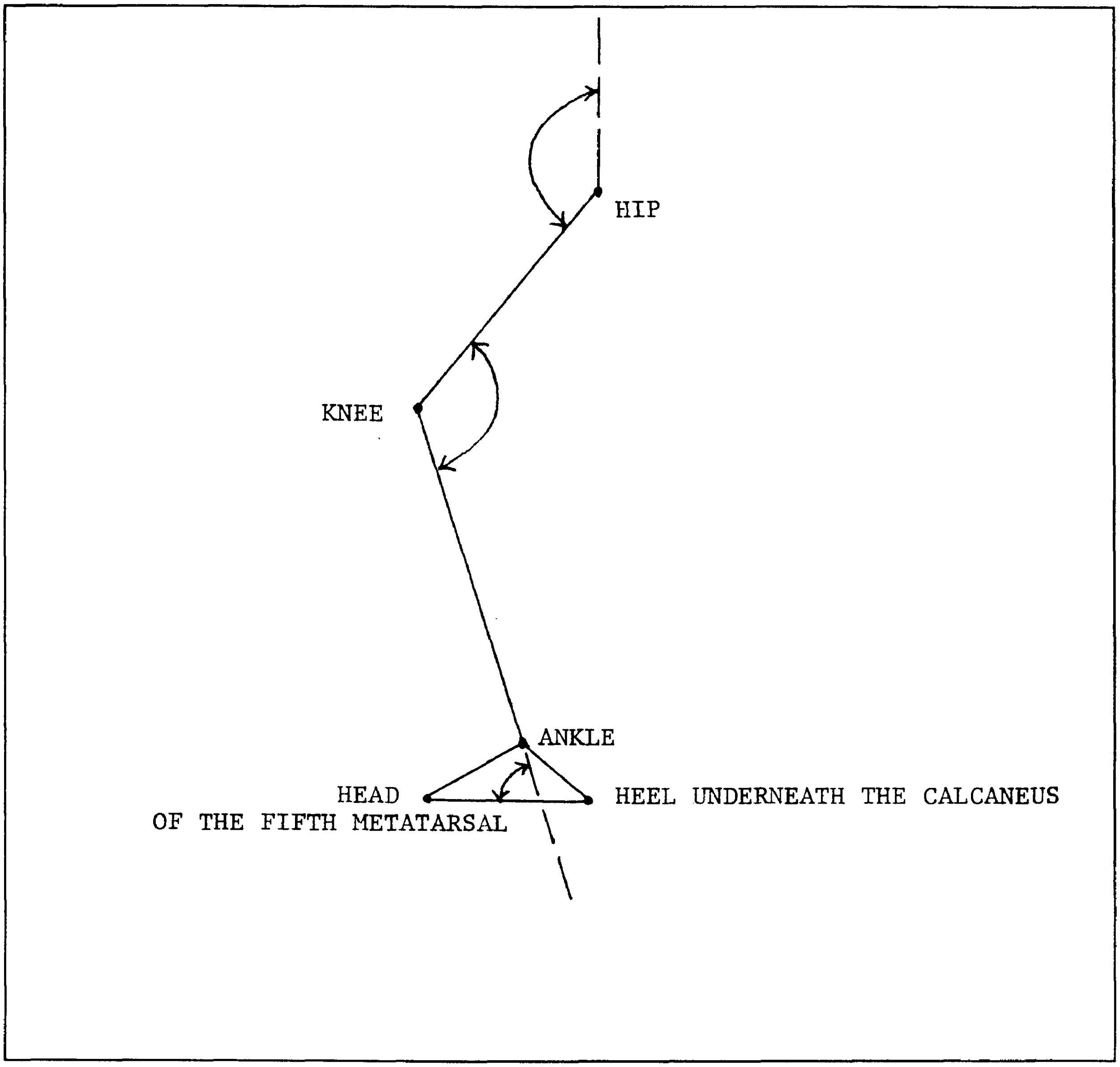

Figure 8. Conventions used for the ankle, knee, and hip angles.

lateral joint line of the knee. Their intersection was the vertex of the angle. PEAK2D Software provided us with the right hip angle frame by frame. The heel strike frame and the toe off frame were used for these measurements. These angles were measured in degrees.

Figure 8 presents all these above angles.

Right tip toe velocity between heel strike and tip toe ground contact. The PEAK2D software provided us with the displacement of the right tip toe from the heel strike to right tip toe ground contact. The time elapsed was calculated by counting the number of frames which elapsed during the movement divided by the frame rate. Then the displacement was divided by the time to obtain the velocity in centimeters per second.

STATISTICAL TREATMENT

For all the above parameters individual values were calculated utilizing the mean of the three acceptable trials in which the speed was 3.8 $\pm$.19 m/sec . Then, the mean and the standard deviation for all subjects were calculated for each parameter, for both conditions of barefoot running and running with running shoes. For each parameter, a dependent t-test was used to compare mean scores for the two situations. The level of significance used was .01. The .01 level of significance was selected because of the large number of variables that were tested.

The test-retest reliability coefficient of the investigator for using the PEAK2D Software and the videographical digitizing process was 0.99. This reliability was determined by digitizing all landmarks for five frames on two separate occasions.

RESULTS

The basic descriptive characteristics of each runner are presented in Table IV. The mean height was 1.6375 $\pm$.071264 m. The mean mass was 57.103 $\pm$6.8921) kg. The overall means, standard deviations, and dependent t-test values for all the parameters measured, for both conditions are shown in Table V. The data were normally distributed and therefore parametric statistics were indicated for the study.

No significant differences were demonstrated in support time, nonsupport time, and stride length between running with shoes and running barefoot. Before and at touchdown vertical heel velocities were significantly higher in barefoot running. However, no statistical differences were noted for both horizontal heel velocities. No significant differences were found for any of the angles measured at touchdown. The same was also observed for strut length and gastrocnemius length.

Maximum knee flexion velocity after touchdown showed no significant difference for running with shoes and barefoot running. No significant difference was observed in tip toe velocity. No significant differences were observed at midsupport and toe off for all the angles measured and for the gastrocnemius length. The strut length was significantly less at toe off in barefoot running, and not significantly different at midsupport. After toe off the maximum hip flexion velocity demonstrated no significant difference between the

Table IV. Basic descriptive characteristics of each subject

Subject	Height (m)	Mass (kg)	Age
1	1.58	48.64	18
2	1.65	62.27	19
3	1.75	66.82	20
4	1.65	59.54	19
5	1.65	55.91	18
6	1.52	47.27	22
7	1.60	54.1	19
8	1.70	62.27	27

Table V. Group Means, Standard Deviations, and t-test values for each selected parameter

Parameters	Barefoot (n=8) X	Barefoot (n=8) s	Shoes (n=8) X	Shoes (n=8) s	t[a]
Stride length(cm)	246.36	5.947	257.88	11.724	-2.56
Support time(sec)	0.252	0.023	0.259	0.019	-1.36
Nonsupport time(sec)	0.438	0.022	0.456	0.024	-2.34
Vertical oscillation of COM(cm)	9.61	1.174	10.16	0.749	-1.29
Max Knee flexion velocity after touchdown(deg/s)	483.54	57.294	546.74	70.109	-2.49
Max Hip flexion velocity after toe off(deg/s)	467.84	71.169	459.21	51.981	0.48
Horizontal Heel velocity before touchdown(cm/s)	181.35	61.452	227.66	85.593	-1.66
Vertical Heel velocity before touchdown(cm/s)	99.05	15.717	71.76	21.607	3.71[b]
Horizontal Heel velocity at touchdown(cm/s)	96.12	30.007	118.11	54.308	-1.08
Vertical Heel velocity at touchdown(cm/s)	91.34	35.276	46.82	30.784	3.86[b]
Tip toe velocity (cm/s)	166.62	30.201	186.48	68.135	-0.84

Strut length at touchdown(cm)	85.0	4.145	85.37	4.651	-0.75
Strut length at midsupport	81.99	3.828	82.63	3.763	-0.99
Strut length at toe off(cm)	87.67	3.871	89.51	4.104	-6.28[b]
Hip angle at touchdown(deg)	157.24	2.879	157.67	3.731	-0.73
Hip angle at toeoff(deg)	210.39	4.082	211.06	3.929	-0.69
Knee angle at touchdown(deg)	167.85	2.84	169.02	5.123	-0.78
Knee angle at midsupport(deg)	152.79	4.724	150.27	5.58	1.90
Knee angle at toe off(deg)	166.05	6.652	167.99	5.46	-1.60
Ankle angle at touchdown(deg)	96.07	14.259	88.04	10.83	1.73
Ankle angle at midsupport(deg)	86.8	3.399	89.2	5.079	-1.04
Ankle angle at toe off(deg)	125.09	12.648	125.76	8.803	-0.32
Gastrocnemius length at touchdown(%)	6.54	2.63	5.16	2.068	1.59
Gastrocnemius length at midsupport(%)	3.75	0.915	4.02	1.348	-0.51
Gastrocnemius length at toe off(%)	11.26	2.317	11.55	1.562	-0.77

[a]df=7.
[b]$p<.01$.

two conditions.

In addition, no significant difference was found in vertical oscillation of the center of mass. The vertical coordinates of the center of the mass for the running cycle for all eight subjects are plotted for both conditions (Appendix A). It's obvious that the movement of the center of the mass in the vertical direction varied to a greater extent during the barefoot condition.

Although, significant differences were found only for the strut length at toe off, all the group means for the parameters (ankle & knee angles, gastrocnemius & strut length) measured at touchdown, midsupport and toe off, are plotted in bar graphs included in Appendix B.

Finally, the relationship between the ankle angle and the knee angle, during the running cycle for both conditions, are illustrated in Appendix C for each subject. These graphs illustrate the movement changes that occur during the running cycle.

DISCUSSION

The present study resulted from a need to better understand the anatomical and mechanical adaptations which occur in the lower extremities in barefoot running versus running with running shoes. Previous studies have asserted that the rigid system of footwear between the foot and the surface does not allow the human foot to react properly during impact (Robbins & Hanna, 1987; Robbins et al, 1988). Other studies have shown increased impact forces while running barefoot (Clarke et al, 1983; Nike Sport research Review, 1988), which result in significant differences mainly in rearfoot kinematic variables (Clarke et al, 1984). This study, using a videographic kinematic approach, is adding more information to the available literature on the reaction of the human body to running with and without running shoes. This should help to better understand the shock absorption properties of the lower extremities.

After appropriate conversions for measurement techniques the results of our study are in close agreement with results reported in other studies involving running with running shoes. Stride length (2.68 m to 2.58 m), support (23 msec to 26 msec) and nonsupport (47 msec to 46 msec) times, and vertical oscillation of the center of the mass (10.9 cm to 10.1643 cm) are similar to values published by Williams (1986) and Milliron & Cavanagh (1990). Angular values are also in close agreement (hip at touchdown = 155 deg to 157.7 deg, hip at toe off = 212-204 deg to 211 deg, knee at touchdown = 160-170 deg to 169 deg, ankle at touchdown = 79-96 deg to 88 deg, ankle at toe off = 121-113 deg to 125.76 deg) with published values by Williams (1986), and Milliron & Cavanagh (1990).

Available literature describing comparisons between barefoot and running shoes in the sagittal plane is limited to two other studies (Clarke et al, 1983; Bates et al, 1978). However, Clarke et al focused on biomechanical measurement of running shoe cushioning properties, and the study of Bates et al was conducting using a treadmill and focused basically on rearfoot movement.

Although, no significant differences were found for the horizontal heel velocity at touchdown, the mean value was greater in running with running shoes when compared to barefoot running. A similar trend has been found by Clarke et al (1983). The significant differences in the vertical heel velocity before and at touchdown, probably is the reason for the higher peak impact forces in barefoot running reported in the literature (Nigg, 1986; Nike Sport Research Review, 1988). Our findings showed no significant differences for the ankle, knee, and hip angles at touchdown, which was contrary to the results of Clarke et al. However, the trends for these means were similar to those reported by Clarke et al (1983) and Bates et al (1978). The means indicated more plantarflexion and less knee extension in barefoot running. These compensations seem appropriate in order to decrease stiffness of the lower extremities. In addition, the strut length mean was smaller at touchdown, which also supports this idea. As knee and ankle angles decrease, strut length decreases also.

Although, the maximum knee velocity after touchdown showed no significant difference, the trend of a smaller velocity in barefoot running (483.5396 deg/s barefoot to 546.7437 deg/s in shoes) is in agreement with Clarke et al (1983) (495 deg/s to 554 deg/s). Clarke et al have found that maximum knee velocity after touchdown increased as midsole hardness increased and explained that as a logical adaptational response to the initial stiffness of a harder shoe. However, this didn't happen between barefoot running and running with running shoes. It would then appear from Clarke's data that the barefoot condition had a better "cushioning" effect as demonstrated by the maximum knee velocity after touchdown. This could support the theories presented by Robbins & Hanna about the rigid system of footwear.

Tip toe velocity between heel strike and toe ground contact revealed no significant difference. The mean value was smaller in barefoot running due to the larger mean in the ankle angle at touchdown.

No significant differences were found at midsupport for any of the parameters measured. However, the strut length mean was smaller in barefoot running which indicated a relative shortening of the extremity. At toe off, our results showed a significantly longer strut length in running with running shoes. Although, hip, knee, and ankle angles exhibited no significant differences, their means indicate less hip flexion, more knee extension, and more ankle plantarflexion in running with running shoes. These angular changes lead to the significantly larger strut length, and to a higher and larger projection during the nonsupport time. As a result, bigger (nonsignificant) means were exhibited in support time, non support time, stride length, and vertical oscillation of the center of the mass. These results showed that running shoes helped the lower body to act more efficiently as a spring in order to generate more energy for the propulsive phase.

Gastrocnemius length mean values in running with running shoes were larger than those reported in the literature (Milliron & Cavanagh, 1990). Although Milliron and Cavanagh used EMG to confirm gastrocnemius length changes, in this study no EMG values were available simultaneously with the estimates of muscle lengths in order to confirm the observations made.

The results of our study revealed some kinematic differences between running barefoot and running with running shoes. The approach of the heel to the ground for the heel strike and the reduced strut length at toe off, shows that the lower extremities kinematics change in order to compensate for the two different loading conditions. If movement patterns changed, it can be assumed that the load distribution changes as well. It may be that changes in running mechanics occur because of protection of some elements of the musculoskeletal system. Related research (Nigg, 1986; Nigg et al, 1981) has shown that mechanical strategies can be employed to decrease overloading of the locomotor system in order to prevent injuries. The running shoe has been involved in this process. However, further research needs to be performed, mainly in the evaluation of the internal forces involved in order to understand why in some Pacific islands Indians never wear running shoes and foot injuries are unknown for them. Certainly, if they were to wear shoes, they would change their kinematics, but it is unknown if this is desirable.

Additionally work still needs to be performed in order to determine the internal forces produced. Neurophysiological or mathematical modelling could be used for such an analysis.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

The purpose of this study was to kinematically describe the movements of the lower extremities in running with running shoes and running barefoot. Another purpose of this study was to identify and compare the anatomical and mechanical adaptations that occur. Seven college age females, members of the University of Nebraska at Omaha cross-country team, and one local competitive long-distance female runner 27 yrs old, were subjects of this study. All subjects were free of any physical disability that could have caused an impaired performance.

All subjects completed one testing session consisting of three acceptable trials each with and without their running shoes. A trial was defined as acceptable when the speed of the subject was 3.8 $\pm$0.19 m/sec and a complete running stride was in the field of view of the camera. Videography (60 fields /sec) was used to film the subjects from the sagittal view. The data capture, digitizing, data calculations, and display were performed by using the Peak Performance Technology PEAK2D Software running on a Zenith 80386 computer. A SONY 1341 Trinitron monitor and a Panasonic AG 7300 video cassette recorder controlled by the Zenith computer, were used to digitize the videography data.

The results obtained from the analysis of the parameters used are summarized as follows:

1. Significant differences between conditions were found for the vertical heel velocities before and at touchdown, and the strut length at toe off.

2. No significant differences between conditions were found for the remaining parameters measured.

3. The measured values for running with running shoes were in close agreement with other reported values (Williams, 1986; Milliron & Cavanagh, 1990; Mann & Hagy, 1980).

4. Results comparing barefoot running and running with running shoes were similar to those published in two related articles (Bates et al, 1978; Clarke et al, 1983).

CONCLUSIONS

For the sample of subjects in this study, the following conclusions were made:

1. Removal of running shoes indicated that the human spring apparatus of the lower extremity tends to shorten at touchdown and during the support phase to diminish shock (due to a lack of cushioning).

2. Running shoes helped the runners to exhibit sufficient forward thrust and drive in order to project their bodies more efficiently during the nonsupport phase.

3. These changes in running mechanics could be attributed to the protection of some elements of the musculoskeletal system

due to the two different loading conditions.

RECOMMENDATIONS

From the findings of this study several recommendations were made concerning further research on comparisons of running barefoot versus running with running shoes in order to better understand the mechanical and anatomical changes involved.

1. Future studies should employ appropriate methods for a detailed determination of the internal forces. Neurophysiological or mathematical modeling could be used for such an analysis.

2. A longitudinal study should be conducted for better evaluation of the effects of barefoot training on injuries and performance.

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APPENDIX A

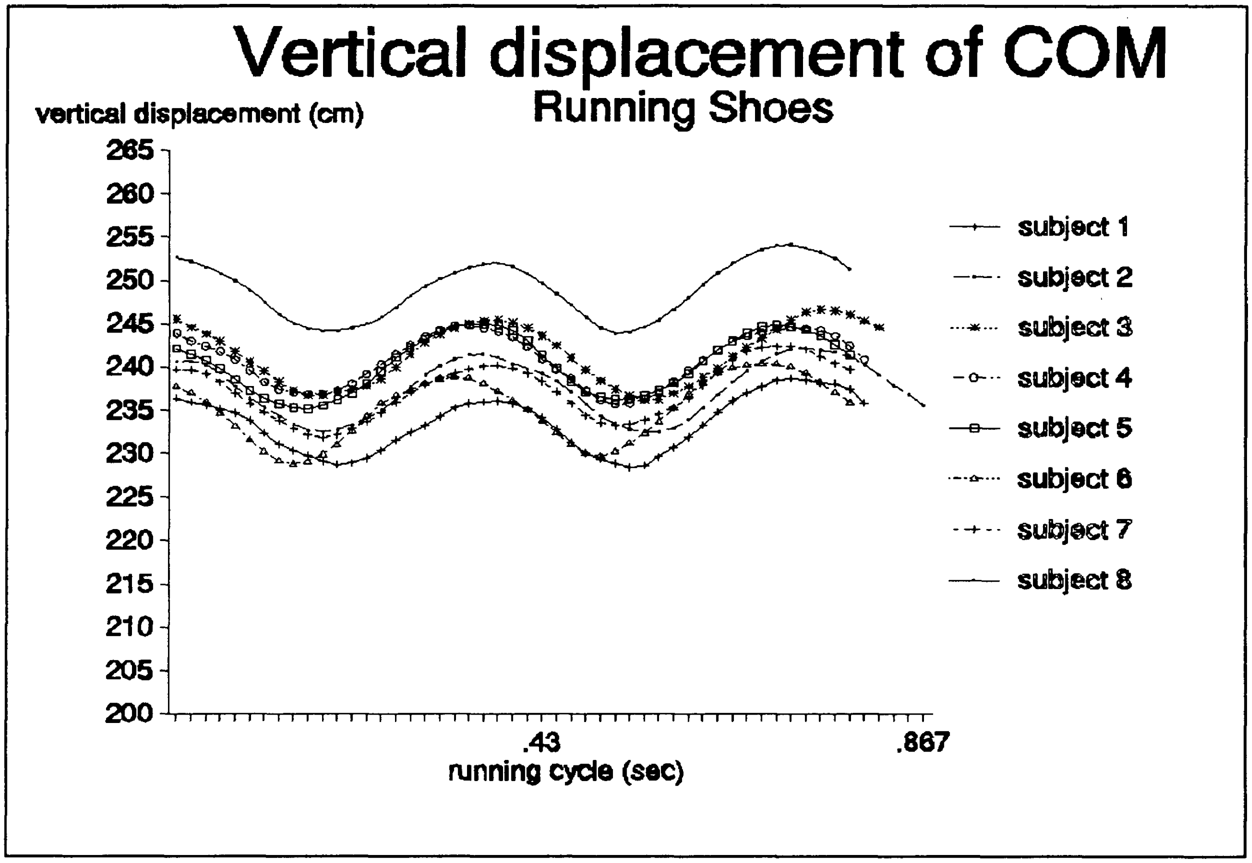

Figure 9. Vertical displacement of the center of the mass for all the subjects for running with running shoes over the running cycle.

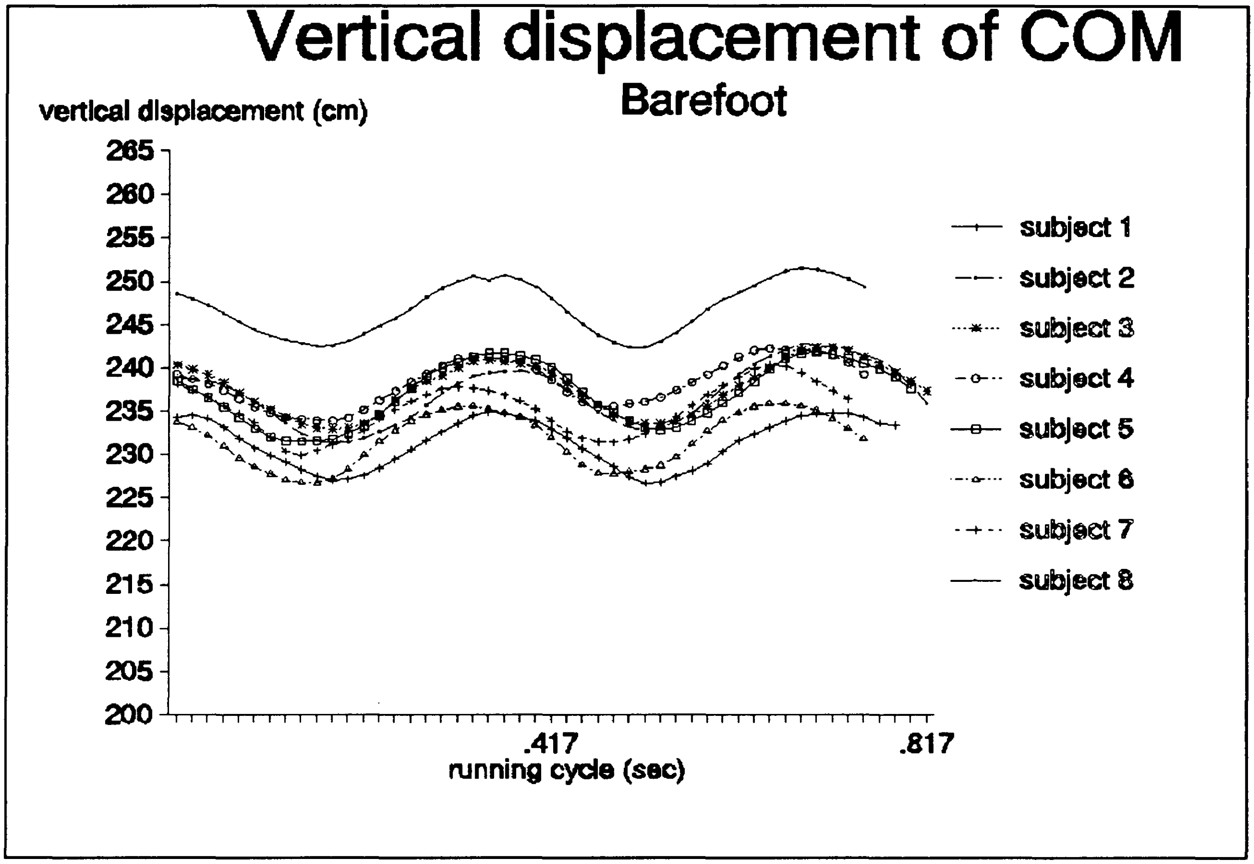

Figure 10. Vertical displacement of the center of the mass for all subjects for barefoot running over the running cycle.

APPENDIX B

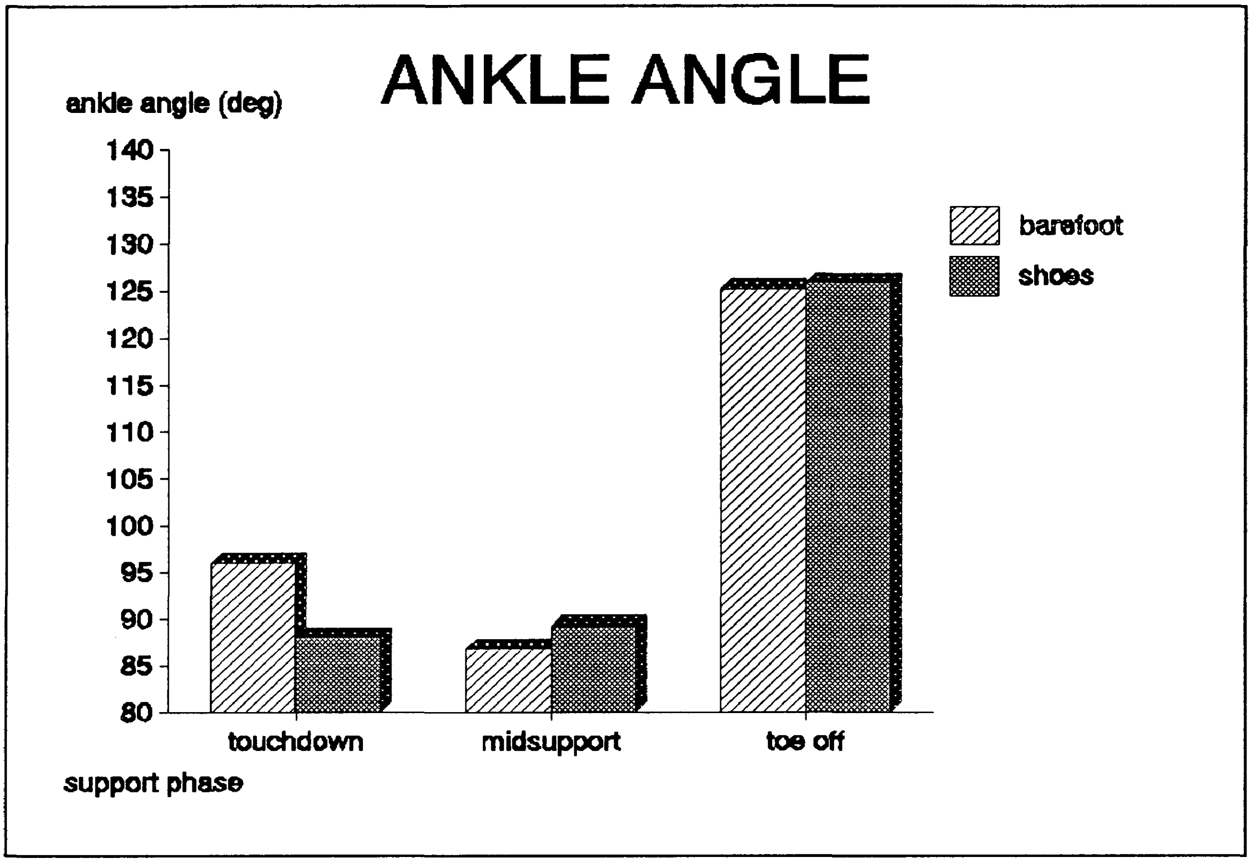

Figure 11. Illustration of the differences in ankle angle means at touchdown, midsupport, and toe off, for barefoot running and for running with running shoes.

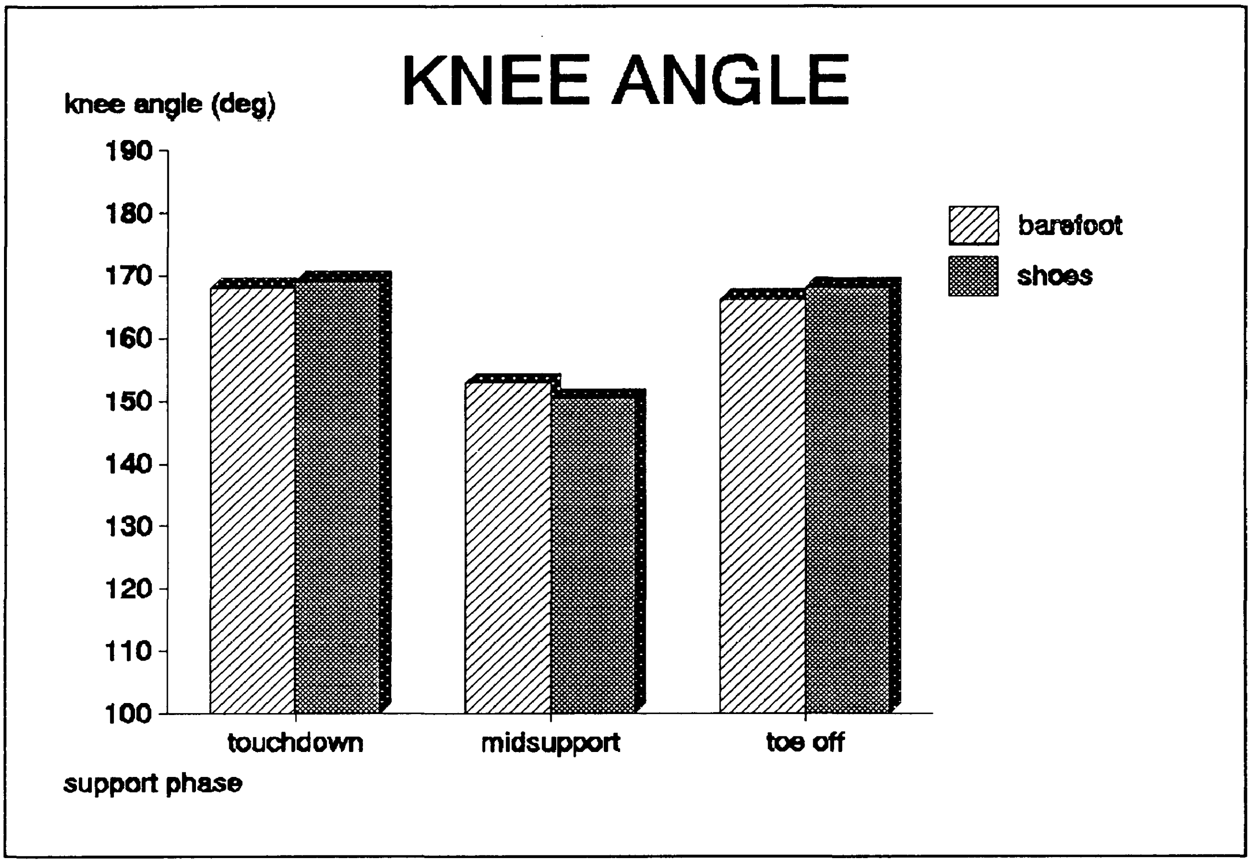

Figure 12. Illustration of the differences in knee angle means at touchdown, midsupport, and toe off, for barefoot running and for running with running shoes.

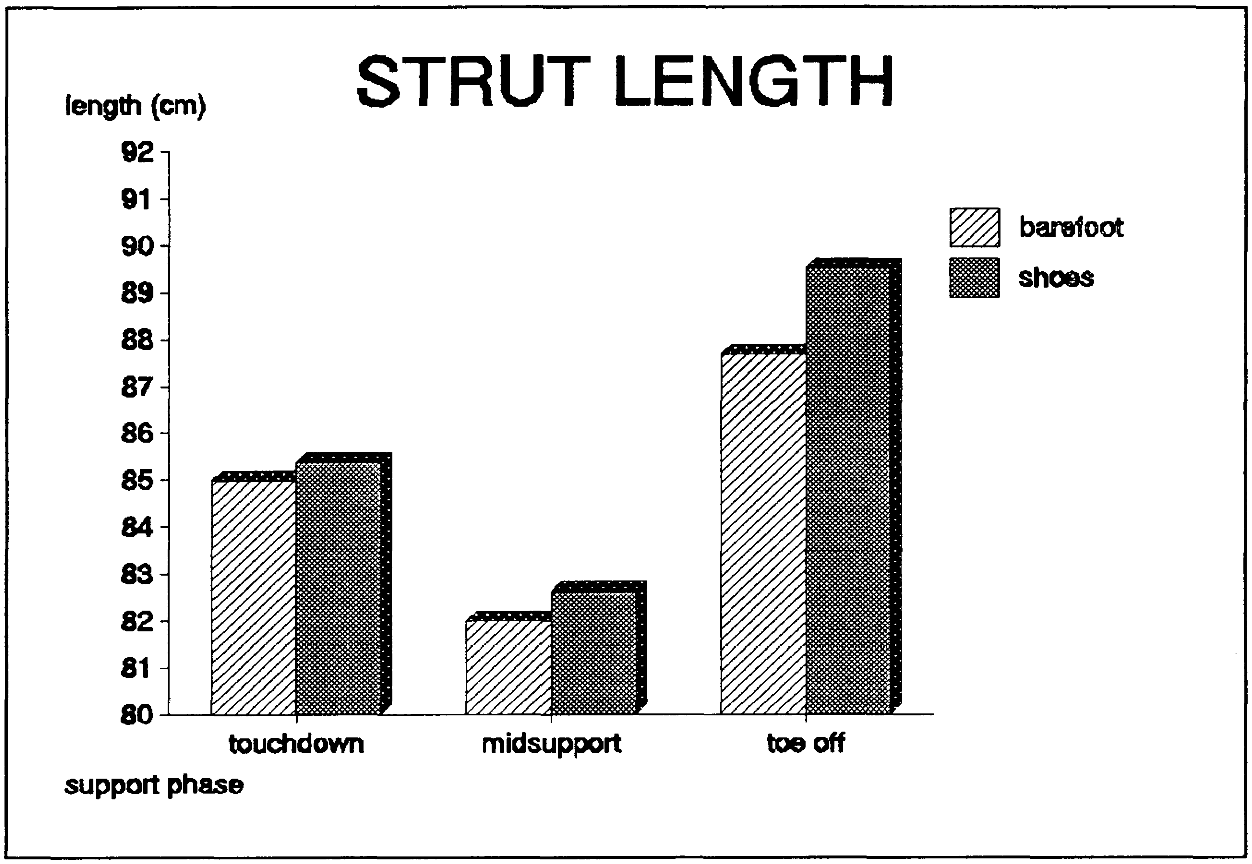

Figure 13. Illustration of the differences in strut length means at touchdown, midsupport, and toe off, for barefoot running and for running with running shoes.

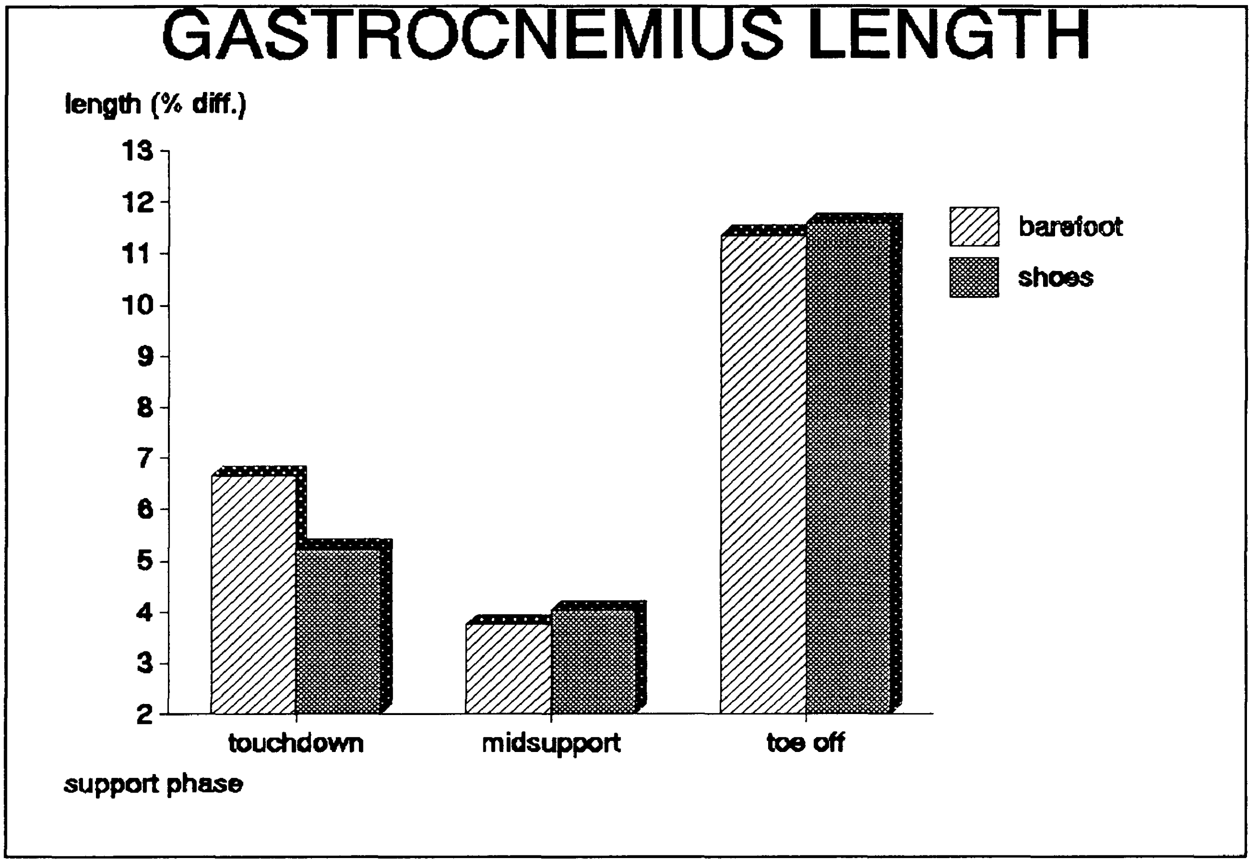

Figure 14. Illustration of the differences in gastrocnemius length means at touchdown, midsupport, and toe off, for barefoot running and for running with running shoes.

APPENDIX C

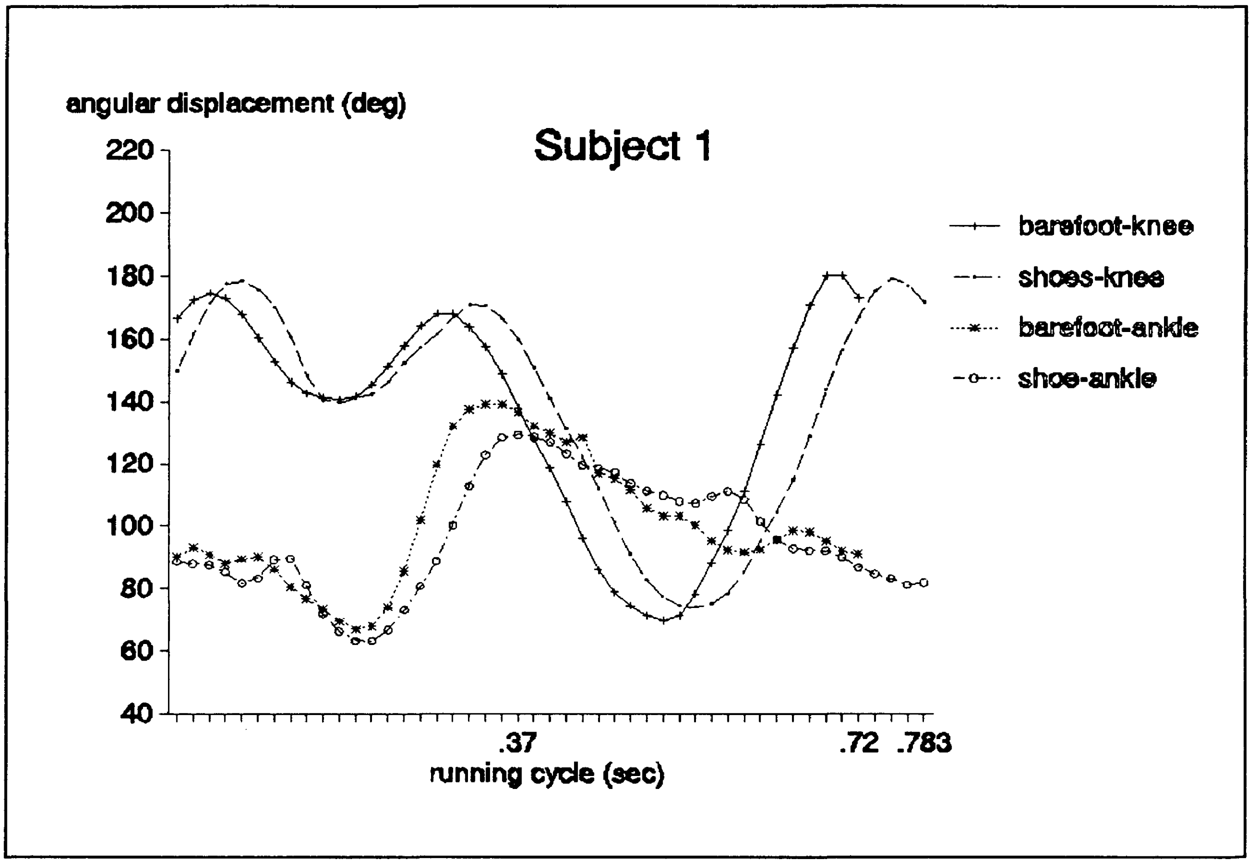

Figure 15. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 1

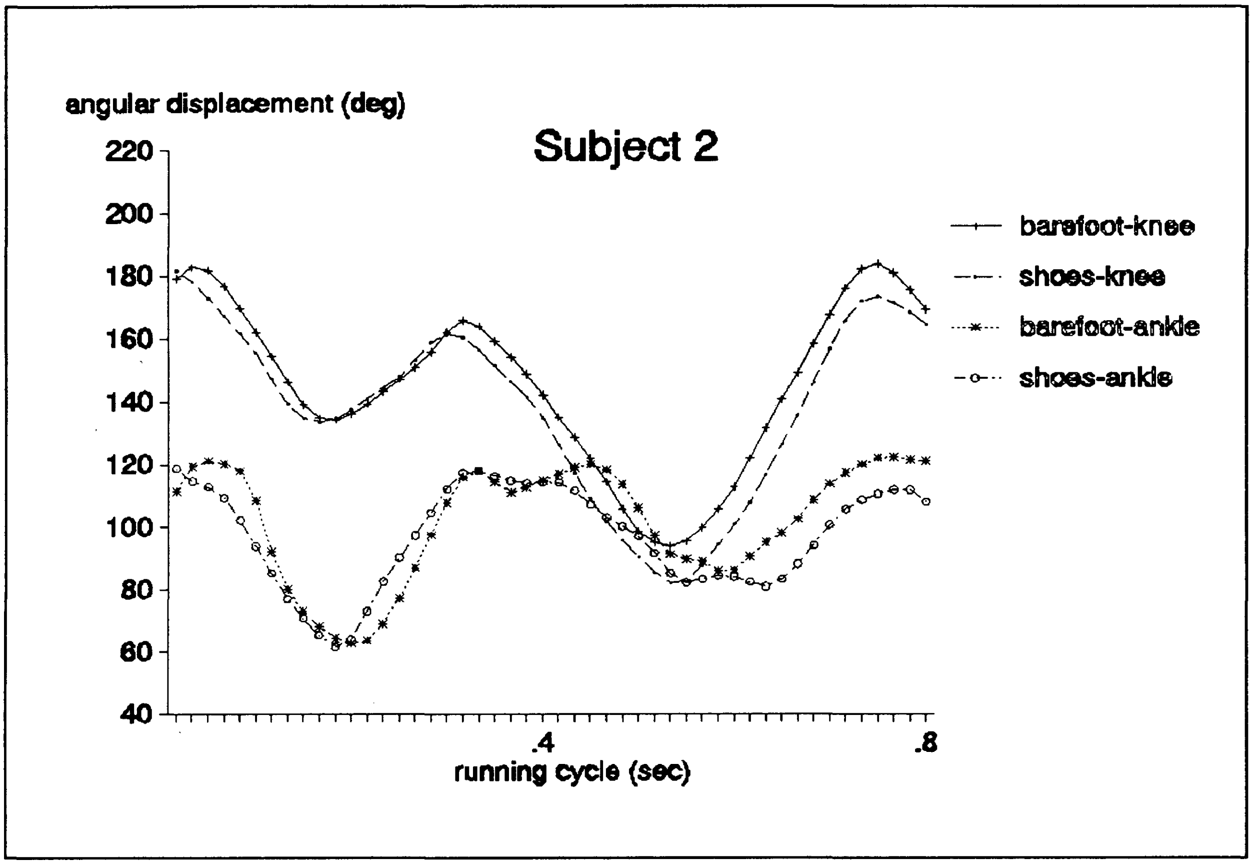

Figure 16. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 2

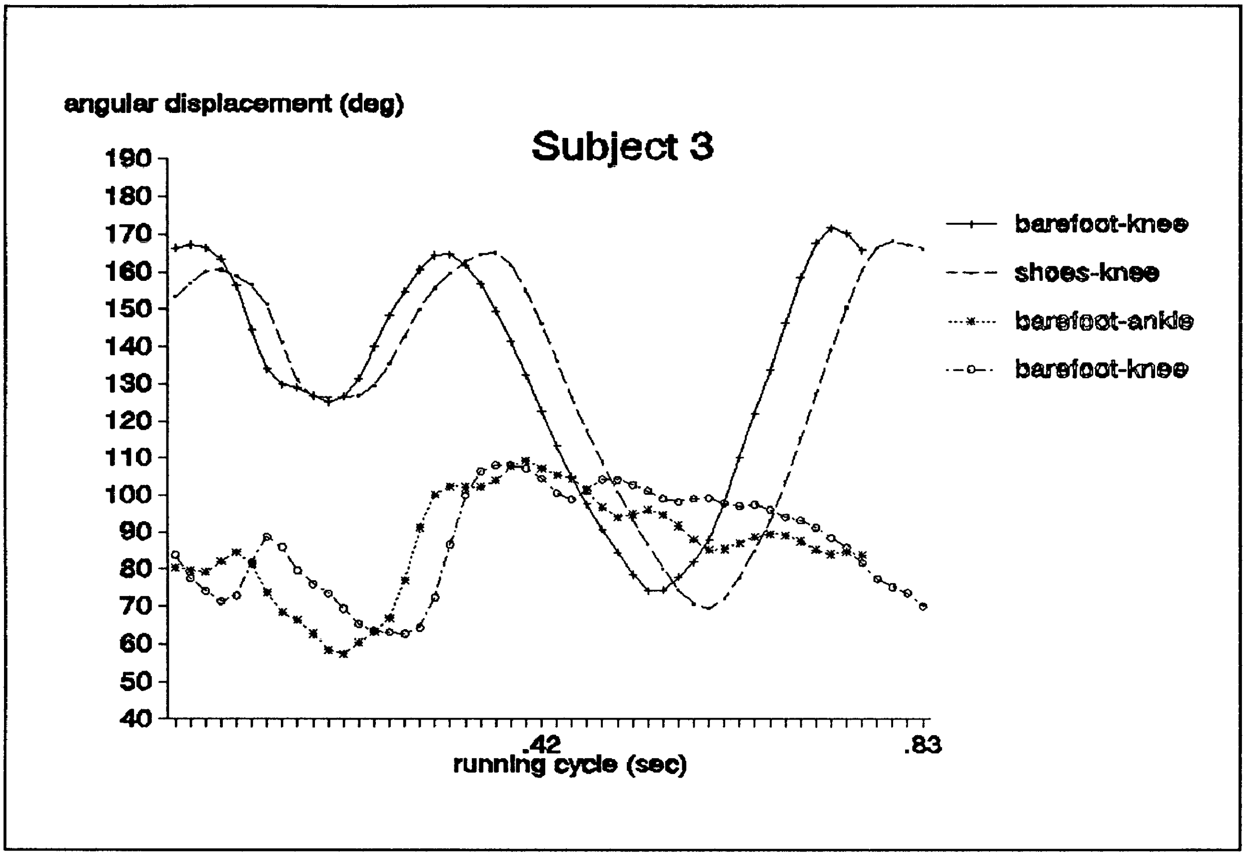

Figure 17. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 3

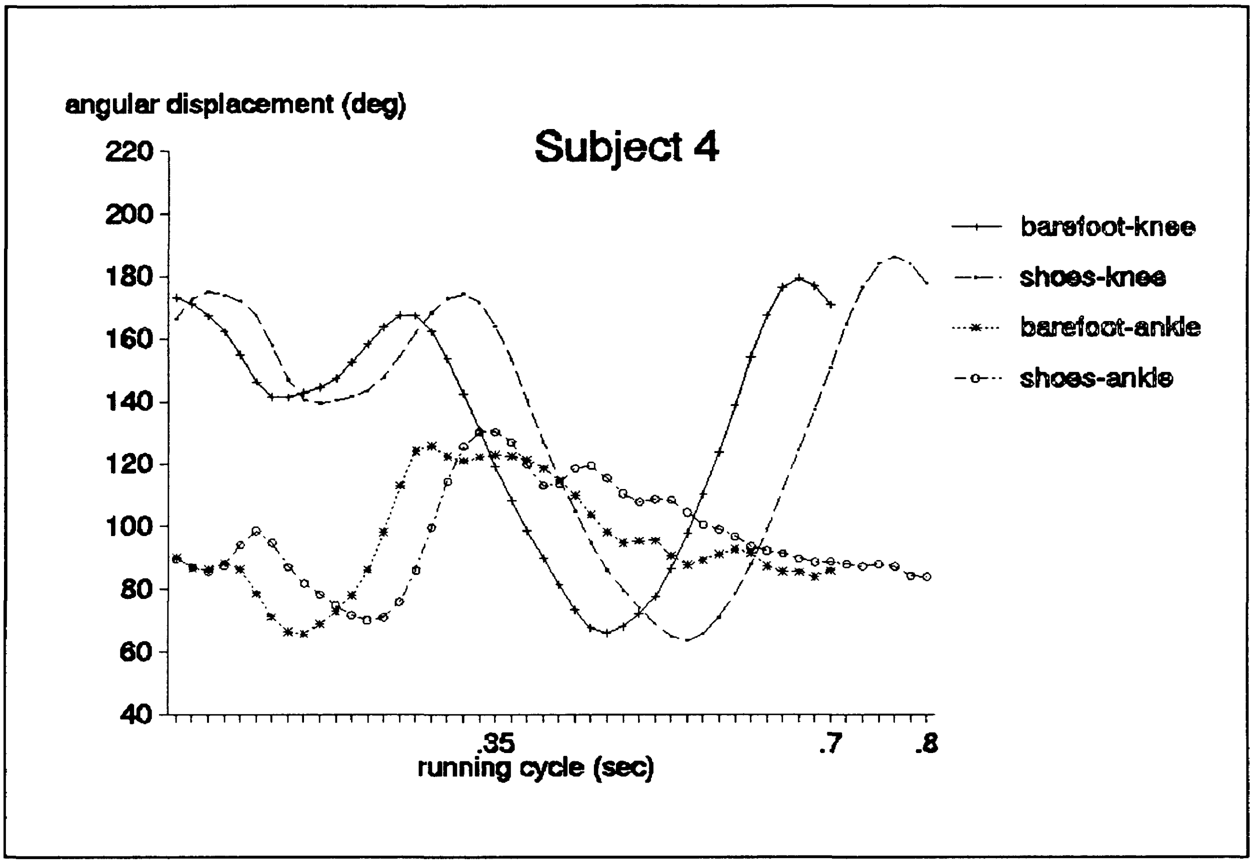

Figure 18. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 4

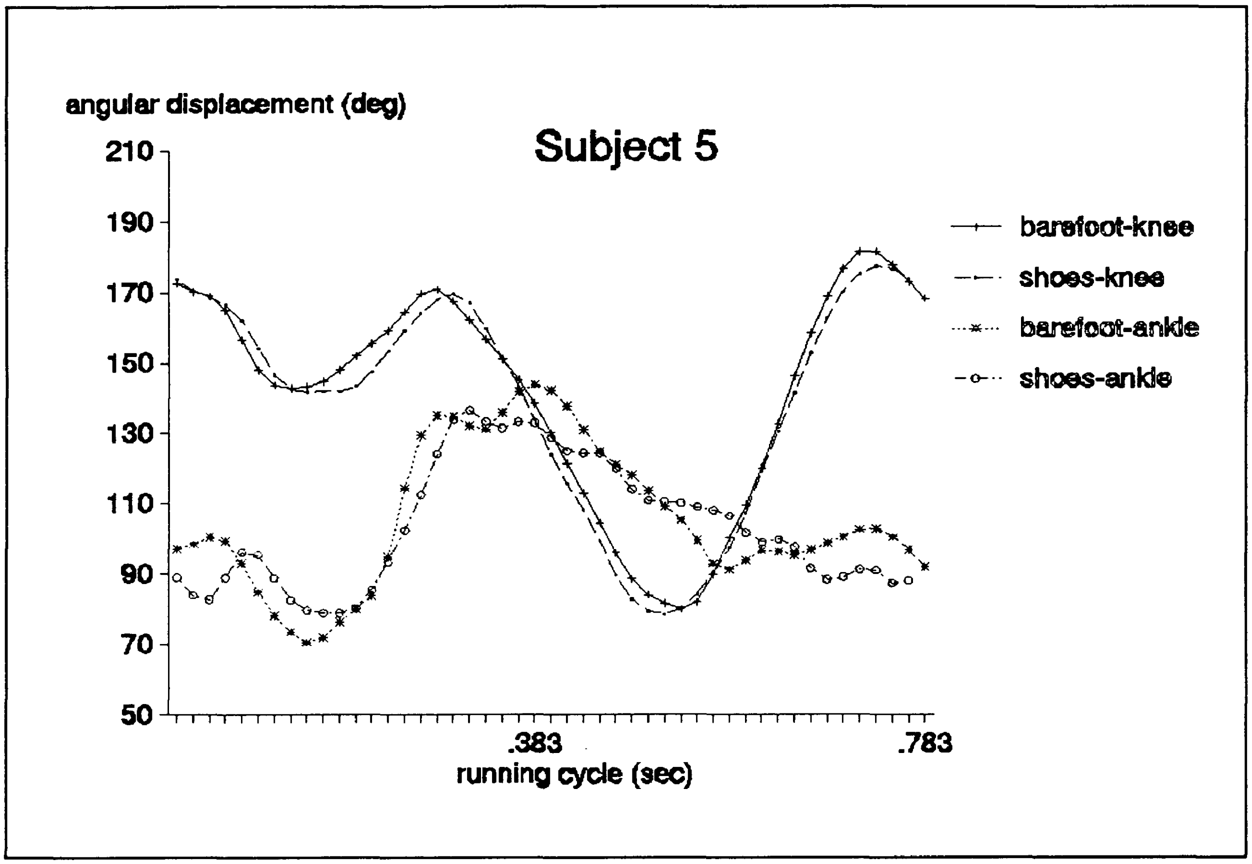

Figure 19. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 5

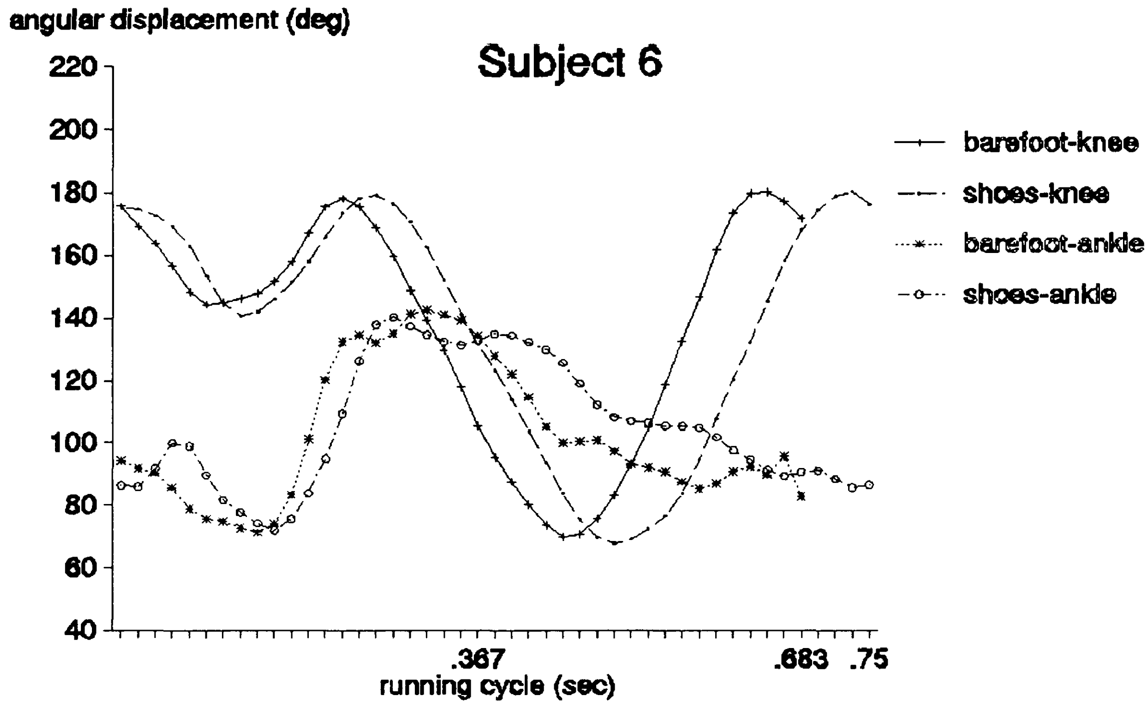

Figure 20. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 6

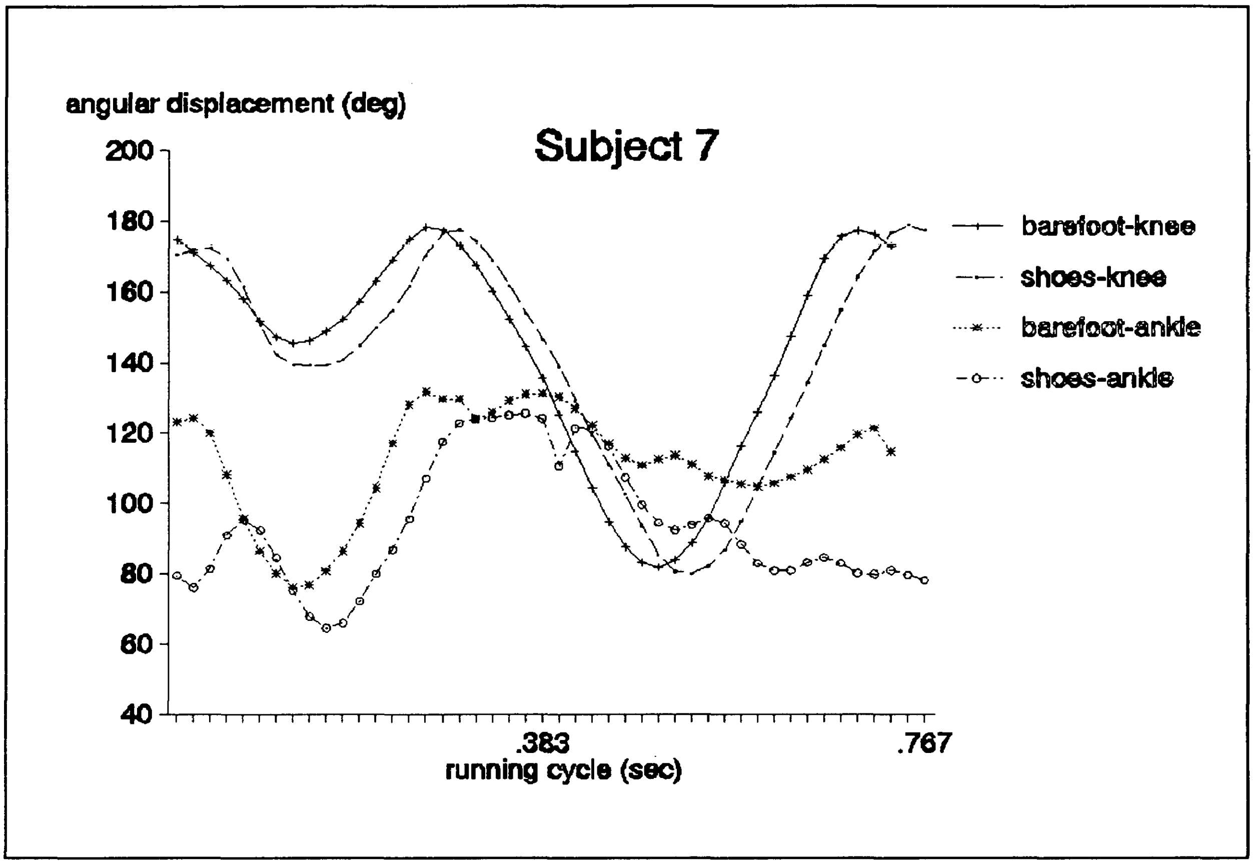

Figure 21. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 7

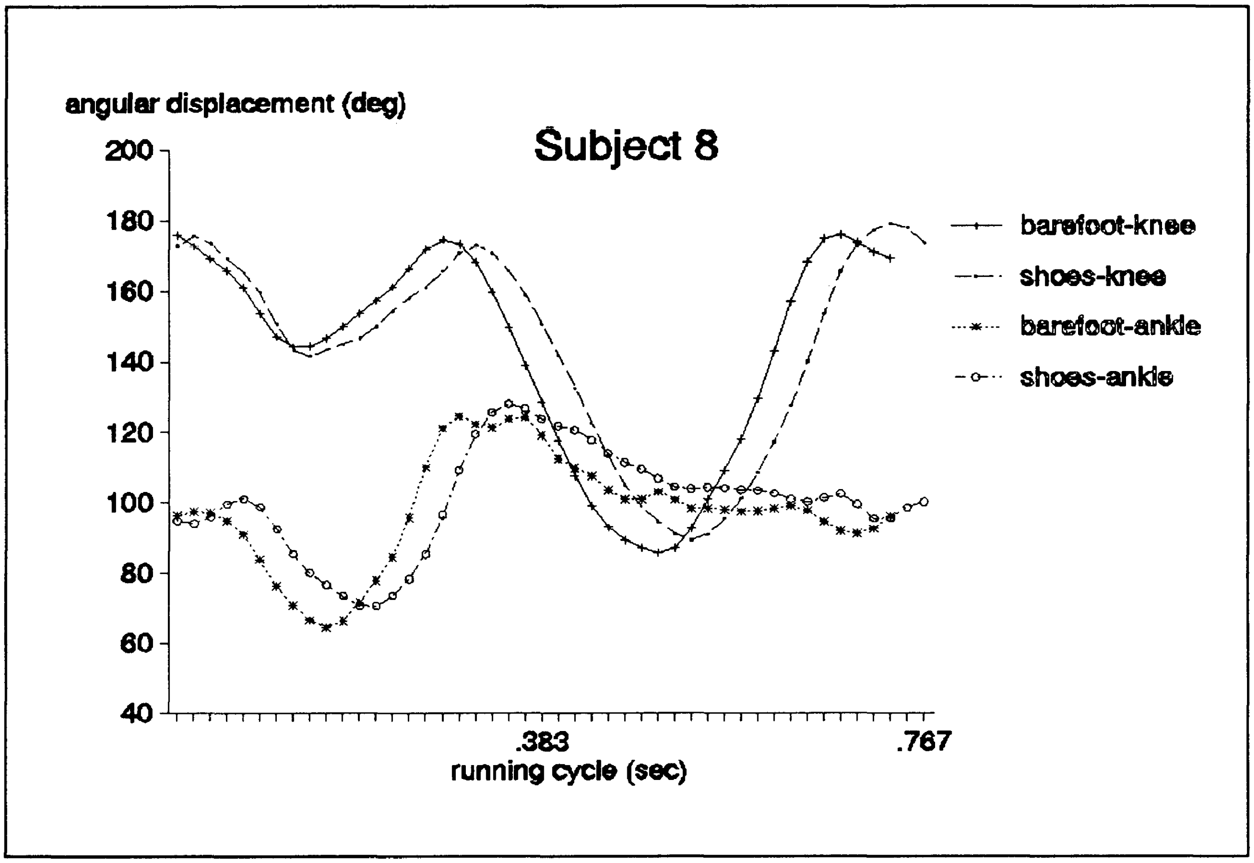

Figure 22. Angular displacement of the knee and ankle angles during the running cycle for barefoot running and for running with running shoes - Subject 8