This is to certify that the

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Ground Reaction Forces And Centers Of Pressure

For A Female Distance Runner

presented by

Sandra L. Gregorich

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GROUND REACTION FORCES AND CENTERS OF PRESSURE FOR A FEMALE DISTANCE RUNNER

by

Sandra Lee Gregorich

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ABSTRACT

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This study examined the ground reaction forces and center of pressure patterns for barefoot and shod conditions of a female distance runner. The need for the scientific analysis of gait is evident in its possible applications to various populations. Amateur and professional athletes, the elderly, and those with gait dysfunction can all benefit from an increase in the existing pool of asymptomatic or normal data. Methods of analysis included comparisons of center of pressure plots, maximum loadings, heelstrike loading, percent of stance for loadings, anterior-posterior crossover, and duration of stance for barefoot and shod trials. Very few substantial differences were found between barefoot and shod conditions. The greatest variation was the percent of stance in which the heelstrike loading occurred, 3.1% for barefeet and 6.1% for shod trials. Possibly the difference could be due to the greater landing area of the shoe and also the material of which the sole is made. Similarities included: 1) increased velocity during the propulsive phase; 2) maximum vertical loading of 2.8 - 3.1 times body weight at 41.1%-43.7% of stance; 3) heelstrike loading of 2.2 - 2.5 times body weight; 4) consistency of stride duration; and 5) the anterior-posterior crossover occurred at an average of 49.5 - 45.6 percent of the stance phase. Increased knowledge of asymptomatic gait can be used to further shoe design, improve rehabilitative techniques, design better prosthetics, and retrain those with gait dysfunction.

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Definitions

Biomechanics - Application of physics and engineering techniques and theories to human motion.

Kinematics - Study or description of motion dealing with displacement, velocity, and acceleration.

Kinetics - Study of forces initiating, altering, and stopping motion.

Temporal Analysis - Deals with the timing or rhythm of various aspects of performance.

Displacement - A change in position.

Ground Reaction Forces - The three-dimensional reactions of the ground to the force applied by a person in the stance phase of gait.

Stride - The fundamental cycle of running or walking. The interval between two successive initial contacts of the same foot. Divided into stance and swing phases.

Stance Phase - The time period in which the foot is in contact with the ground.

Swing Phase - The time period during which the foot leaves the ground and moves ahead of the body prior to contact.

Heelstrike - The point at which the greatest force initially is recorded and occurs generally within 10 ms of foot contact. Heelstrike is used to describe the first initial peak of ground reaction force (z direction) regardless of what part of the foot initially contacts the force plate.

Midstance - The point at which the shank is perpendicular with the ground.

Propulsive Phase - To drive forward by means of force that imparts motion.

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Moment - A turning force.

Translation - Movement in which there is straight line motion.

Screw Axis - The instant center of rotation for plane motion (Kinzel, Hall, & Hillberry, 1972).

Wrench Axis - The resultant force vector with its associated parallel torque component (Shimba, 1984).

Center of Pressure - The intercept of the result of the screw axis resultant and the force plate resultant.

Chapter I

Introduction

Human locomotion has been described subjectively and scientifically since approximately 320 B.C. when Aristotle began studying and classifying animal movement. Although gait analysis has a long history, a definitive quantitative model is still being sought. Human locomotion, defined in this context as walking or running, has been studied in many disciplines including kinesiology, neurophysiology, and biomechanics to name a few. Children begin to walk, unless there is a pathology, and soon after, run with little attention drawn to their form (Wickstrom, 1983). The ease with which most children and adults acquire the universal skill of running makes it appear to be simple. However, both walking and running are complex three-dimensional motions.

According to Gallahue (1982), "Walking has often been defined as the process of continually losing and regaining balance while moving forward in an upright position" (p. 180). Walking can easily evolve into running since arm and leg movements of the body in both activities have a similar pattern (Keogh & Sugden, 1985). The main difference between the two gaits is an airborne phase, or flight phase, in running. Walking and running are mentioned together here because both gaits have been studied employing similar techniques. Running and walking, or gait, is made up of repetitive cycles called strides and each stride is further divided into stance and swing phases. A stride can be thought of as the time between two footstrikes of the same foot. The stance phase, measured by a force plate, is the time the foot is in contact with the ground. The swing phase occurs when the foot leaves the ground and moves ahead of the body prior to contact.

Many investigators have undertaken the task of describing the mechanics of locomotion. Studies ranging from ground reaction forces during a run (Cavanagh & LaFortune, 1980; Cavanagh, Andrew, Kram, Rodgers, Sanderson, & Hennig, 1985; Dickinson, Cook, & Leinhardt, 1985; Frederick & Hagy, 1986; Hamill, Bates, & Knutzen, 1984; Hamill, Bates, Knutzen, & Sawhill, 1983; Munro, Miller, & Fuglevand, 1987;) to moments of force at various joints (Seireg & Arvikar, 1975; Verstraete, 1988; Winter, 1983) are found in the literature. The importance of this type of research is demonstrated through demands for improved shoe designs, increased understanding of injury by physicians, improved rehabilitation programs, better built prosthetics, and safer, more efficient training techniques.

Need for the Study

The need for this study is evident in its possible applications to various populations. Sport injuries, especially those due to overuse, are increasing in frequency in professional, amateur, and recreational athletic populations (Cavanagh, 1980; Clemen, Taunton, Smart & McNicol 1981; Subotnick, 1977). Compounding poor technique and lack of proper instruction with low levels of fitness, more sport injuries may be seen, particularly in the growing ranks of the recreational/weekend athlete. For improved care to be given and better protective equipment to be provided, limb and joint functions must be documented to obtain a range of normative data. Accurate knowledge of the total motion permitted by two body segments can supply information that will improve current methods of support and replacement for malfunctioning joints, as well as improve rehabilitation exercises for an injured or diseased joint (Kinzel, Hall,

& Hillberry, 1972). Knowledge regarding such aspects of "average" gait parameters, support in knee braces, and support without limiting performance is sparse.

Our increasing older population has brought yet another area of concern for biomechanists. Treatment of arthritic and neuromuscular diseases and prevention of hip and other injuries have become major concerns for health professionals. To understand gait problems and contributing musculoskeletal pathologies a pool of data for "normal" function needs to be established for the movement of limbs and joints in different activities. Large forces can be generated across joints and inadequate knowledge of their magnitudes and lines of action might lead to "imperfect" replacements, or replacements that may break down easily under daily stresses. Thus, the design of implants and/or surgical procedures to reconstruct a problem hip joint can be facilitated and improved in part with information on the daily biomechanical stresses the reconstructed hip will undergo (Crowninshield, Johnston, Andrews, & Brand, 1978). Analysis of "normal" or acceptable dynamic gait can play a part in increasing the body of knowledge to better understand some pathologies.

An additional population which would benefit from research contributing to the pool of normal data are those afflicted with gait dysfunction. For example, through the use of a force plate and knowledge of asymptomatic gait cerebral palsy patients are being retrained to walk. As the person steps on the force plate he/she is supplied with immediate feedback by tones whose pitches indicate the correctness of the forces being applied by the foot to the force platform. Thus the normal data pool shapes the learning of a more functional walking technique. Similarly, improved knowledge of normal running parameters could be used to retrain dysfunctional runners.

Unfortunately, there is a lack of research applying three-dimensional analytical techniques to motion. Not only is there a lack of research, but the majority of the two-dimensional research presented in the literature used solely male subjects. Generalizing gait characteristics to women from groups of males or males and females can result in misconceptions, especially since studies done by several researchers (Buckalew, Barlow, Fischer, & Richards, 1985; Chao, Laughman, Schneider, & Stauffer, 1983; Williams, Cavanagh, & Ziff, 1987) have shown differences in stride characteristics between men and women.

Purpose

The purpose of this study was to examine the ground reaction forces and center of pressure patterns of a female distance runner. Specifically, the relative ground reaction forces and centers of pressure for shod and barefoot conditions were compared. A runner with asymptomatic gait was analyzed to increase understanding of normal parameters. The information gleaned from this study will add to the literature on asymptomatic subjects.

Delimitations

The subject in the study was a female distance runner training 35+ miles per week at an eight minute mile pace. The purpose of the study was to examine the center of pressure patterns under two conditions: barefoot and with shoes. Since it was not the purpose of this study to derive statistical norms of center of pressure during running, only one subject was used. While only data on the left foot were collected, symmetry was not assumed. The fact that the left foot was chosen for study was arbitrary. Due to unavoidable circumstances (computer changeovers), the initially proposed biodynamics study was not performed. Anthropometric data were gathered, and targeting and filming using high speed cinematographic procedures were obtained for the original biodynamic study. Reference to these aforementioned data, particularly on the Subject Information sheet (Appendix A), refer almost entirely to the biodynamic study. However, the kinematic and kinetic data and analysis programs are available from the author and author's advisor for future analysis.

Assumptions of the Study

The major assumption of this study was that the athlete did not alter her normal running pattern due to the experimental set-up. The subject was allowed as many practice runs as necessary before data were gathered, and she was required to land on the force platform with her left foot while maintaining a normal stride. A normal stride was defined as one in which the runner did not have to lengthen or shorten her stride to hit the plate and her whole foot contacted the plate. A trained observer watched the subject's stride and foot-force plate contact for each trial. In addition, feedback from the runner to the researcher was given after each trial. Trials for which the runner felt she needed to stretch to reach the plate or shortened her step to hit the plate were not analyzed. Finally in order to establish reliability in the trials chosen for analysis, the film data also was reviewed and used as a screening method. Of eight trials, three were unable to be transferred due to computer malfunction and/or they failed to meet the criteria for normal strides.

Chapter II

Review of the Literature

For hundreds of years social gatherings have included foot races, from the marathons of ancient Greece to the New York and Boston marathons run today. Running and racing are popular forms of recreational, therapeutic, and serious athletic activities. Biomechanics offers exercise science, physical therapy, engineering, osteopathy, and other related fields a technique to study and provide insight into the basic mechanism of movement. Although biomechanics draws on many diverse areas, it is a discipline in itself. Miller and Nelson (1976) defined this science as one which investigates the effects of internal and external forces upon living bodies. To review the literature for biomechanics one must go to journals of engineering, medical science, sport, and biomechanics.

This review of literature encompasses research findings of studies involving female subjects, ground reaction forces and center of pressure. The following chapter is separated into two parts. The first section reviews the history of exercise science investigations of ground reaction forces and female runners. Kinetic methods of three-dimensional gait analysis is the focus of the second section.

I. History

The history of scientific gait analysis begins with the development of photography. Although photographs have been around since the late Renaissance (15th century), photography was not used as a motion analysis tool until the 1800's. In 1878, Muybridge (1955) used a series of cameras set up with trip wires to film a running horse. This series of pictures was the beginning of cinematography. A Frenchman, Marey (1895), took Muybridge's idea further by using a single plate to record a series of exposures. These two men are credited with pioneering cinematography. Today, high speed cinematography enables scientists to gather movement information over very short time intervals.

A second major advance in motion analysis was the development of the force platform. The force platform is the basic tool involved in recording kinetic findings. Most of the investigations reporting kinetic data were performed within the last fifteen years because of the advancements in the development of force platforms and computer technology. Although many advances are recent, the study of gait may have begun with something as simple as examination of footprints in a smoothed garden plot. Researchers including Fenn (1930a, 1930b), Elftman (1939a, 1939b), and Manter (1938) conducted studies that were to become classics in the field of biomechanics. Their work in the 1930's formed the technological basis for the study of ground reaction forces today.

Ground reaction forces have been studied for over 50 years for both sprint and distance running. Measured with a force plate, ground reaction forces are the reactions of the ground to the force applied as a person moves in the superior-inferior, anterior-posterior, and medial-lateral directions and the moments about those primary axes. In 1930, Fenn (1930a, 1930b) pioneered kinematic and kinetic studies of sprint running utilizing a crude force plate. He matched vertical and anterior-posterior impulses to determine changes in mechanical energy. Conceptually, Fenn was one of the earliest investigators to provide a foundation for present day research. Another early investigator of gait was Elftman. In 1939, Elftman (1939a, 1939b) presented methods for calculating the rate of energy transfer across joint centers and rate of change of energy of the legs during walking. One year later, Elftman (1940) analyzed one running stride by utilizing free body diagrams and force-mass acceleration principles similar to those used later by Plagenhoef (1966, 1971), Dillman (1970), and Miller and Nelson (1976). Manter (1938) contributed a classic study that helped form the basis for modern day biomechanics. Manter examined muscle torques of a cat walking by using a combination of moving pictures and a platform that recorded force.

Ground reaction forces recorded by a force platform are useful as descriptive tools to analyze the support phase of running (Cavanagh & LaFortune, 1980; Dickinson et al., 1985; Hamill et al., 1983; Munro et al., 1987; Soutas-Little, Beavis, Verstraete, & Markus, 1987). Often the information gathered aids in improved understanding of the etiology of lower extremity injuries (Gudas, 1980; James, Bates & Osternig, 1978; Subotnick; 1977), improvement in shoe design (Bates, Osternig, Sawhill, & James, 1983; Cavanagh, 1980; Nigg, 1986; Nigg & Bahlsen, 1988; Nigg & Morlock, 1987), and assessment of nonpathological gait (Chao et al., 1983; Soutas-Little et al., 1987; Soutas-Little, Frederickson, Schwartz, & Soutas-Little 1987; Snow, 1990). For the current study, force platform data were gathered to obtain ground reaction forces and center of pressure for the foot.

Although ground reaction force investigations on adult male subjects were more common than those done with adult female subjects, generalizing the findings from males to females would appear to be inappropriate. In gait studies of walking and running, gender-related characteristics often were noted. Chao, Laughman, Schneider, and Stauffer (1983) presented three-dimensional data on walking and noted gender differences in temporal stride characteristics and ground reaction forces. However, age was not controlled for in this study, which contaminated the male/female comparison. Several researchers (Buckalew et al., 1985; Williams et al., 1987) demonstrated that differences existed in the mechanics between adult male and female runners. Williams et al. (1987) found that elite female marathoners "exhibit more hip flexion, greater angular velocities in hip flexion and extension, and longer stride lengths relative to leg length than do their male counterparts" (p. 117). Buckalew et al. (1985) showed that "women spend greater time in the support phase and less time in the nonsupport phase of running than men do" (p. 341). Gender related differences in running have also been observed in children as young as four and five years of age (Fortney, 1983). Even though the analysis was two-dimensional in nature, the differences in running shown in joint angles and angular velocity may extend into adulthood. Several additional studies involved groups of subjects consisting of both males and females (Bahlsen & Nigg, 1987; Cavanagh & LaFortune, 1980; Frederick & Hagy, 1986; Hamill et al., 1984; Rohrle, Scholten, Sigolotto, & Sollbuch, 1984). However, in their research, these investigators did not report any comparison between data on male and female subjects, nor did they mention the possibility of gender-related differences.

Although some comparison of temporal and positional characteristics of elite males and elite females has been performed (Buckalew et al., 1985; Williams et al., 1987), there is a need in the literature for comparing ground reaction forces and centers of pressure. In addition, three-dimensional analysis techniques have not been commonly used (Chao et al., 1983; Kinzel et al., 1972; Soutas-Little et al., 1987; Soutas-Little et al., 1987). A further problem with conclusions concerning the presence or absence of gender differences may be that most females studied were members of a higher skilled, elite population (Bates & Haven, 1973; Bates & Haven, 1974; Buckalew et al., 1985; Haven, 1977; Nelson, Brooks & Pike, 1977; Williams et al., 1987). Elite runners are a group that is unique when compared to "average" runners in terms of the frequency of workouts, speed, and other training factors. Due to emerging evidence of gender differences in mechanics of running and walking, mixed data may not be accurate for describing both males and females.

Though the investigations of Williams et al. (1987) and Buckalew et al. (1985) did compare elite male and elite female performance factors, neither measured ground reaction forces or center of pressure. No studies, with the exception of Soutas-Little et al. (1987), have examined ground reaction forces and center of pressure specifically for "average" females. Moreover, due to the recent technological advances in biomechanics, three-dimensional analysis techniques have yet to be commonly employed to analyze gait. The few exceptions include the work of Soutas-Little et al. (1988), Soutas-Little et al. (1987), Chao et al. (1983), Chao and Rim (1973), Snow (1990), and Verstraete (1988).

II. Kinetics

Cinematography provides descriptive data, but, since forces can not be calculated from position data, this kinematic method is not usually employed alone in the study of gait. A force platform is used commonly in conjunction with kinematic data to provide three-dimensional information on ground reaction forces and moments during the stance phase of running or walking. However, recently the force plate has been used in examining back pain (Johnson, 1990), and in attempting to determine normal ranges of gait (Snow, 1990; Soutas-Little, et al. 1988). Both the reaction of the ground to the force applied by the subject in the x, y, and z orthogonal directions and the moments about these axes are measured by the force platform. By using this information, the center of pressure can be calculated between the ground and the foot. Most of the past biomechanical literature involving gait and ground reaction forces dealt with two-dimensional analyses. Since the majority of motions associated with running occur in the sagittal plane, many researchers observed and analyzed motion occurring in this plane. Seminal studies in two dimensions analyzing gait in a sagittal plane were done by Elftman (1939a, 1939b) and Manter (1938). Elftman's research on walking was a planar description of motion and forces. His methods for calculating forces and moments of the lower limb during walking are still being used today. Manter (1938) was among the first to combine force plate data with cinematography successfully to analyze motion in the sagittal plane. Using the recorded motions and forces, he calculated muscle moments in the sagittal plane in the limbs of a walking cat.

In general it was thought that motion outside the sagittal plane during running and walking was negligible. However, research employing methodology to analyze moments in three dimensions has demonstrated otherwise. The three-dimensional forces and moments of the lower limb during a complete walking stride were calculated by Bresler and Frankel (1948). These researchers emphasized the importance of the nonsagittal components of the joint forces, such as the medial-lateral moment, in providing stability during stance, as well as their effect on the moments at the hip. Using similar methods for computation, Andriacchi and

Strickland's (1985) results agreed with Bresler and Frankel's (1948) analysis that all three components of a moment at a joint were important.

Two-dimensional investigations utilizing female distance runners and ground reaction forces are relatively few in number and those done in three-dimensions are even fewer. Generally, those studies that do exist tend to examine temporal factors such as stride length and percent time spent in the support phase (Bates & Haven, 1974; Buckalew et al., 1985; Nelson et al., 1977) and/or evaluate positional data and its derivative, velocity (Bates & Haven, 1974; Buckalew et al., 1985; Nelson et al., 1977; Ulibarri, 1974). Only one two-dimensional study discussed biomechanical force aspects of female runners. Williams et al. (1987) used ground reaction forces obtained from the force plate to study relative motion of the foot to the ground. Biomechanical variables included: footstrike patterns, peak forces during stance, and asymmetry of forces between right and left feet. Results of the study included vertical ground reaction forces of 3.3 times body weight for elite female distance runners and asymmetry expressed mainly in the mediolateral component of the stance phase.

One group of researchers did combine three-dimensional techniques and force data to observe female gait. Soutas-Little et al. (1987) presented a Dynamic Profile of Female Gait at the 1987 Biomechanics Symposium. The investigators utilized Grood and Suntay's (1983) joint coordinate system to obtain relative three-dimensional motions between the forefoot, rearfoot, thigh, and shank. Moments for the ankle, knee, hip, and the total support moment were also examined. The results indicated that the hip moment differed the most from person to person (Soutas-Little et al., 1987).

A few studies have examined center of pressure for runners and/or walkers (Cavanaugh & Lafortune, 1980; Munro et. al., 1987; Soutas-Little et al., 1987; Snow, 1990). However, with the exceptions of Snow (1990) and Soutas-Little et. al. (1987) center of pressure was used as a method of classifying footstrikes and was not the primary focus of the study. Snow (1990) analyzed a group of nine males and seven females walking and running in both bare feet and shoes. He compared resultant force and torque vectors, their positions and the paths of the intercepts with the force platform surface. Soutas-Little et al. (1987) also compared center of pressure between nonpathological runners and walkers. Her study was unique in that all 27 of the subjects were female and many aspects of gait were examined. Her findings demonstrated that the moment at the hip appeared to be the most sensitive to individual gait variations. The results of the study indicated that individual characteristics for gait could be obtained and that the ground reaction force and center of pressure data supported the existing data on women.

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Unfortunately, there is a lack of research applying three-dimensional analytical techniques to motion. Not only is there a lack of research, but the majority of the two-dimensional research presented in the literature used solely male subjects. Generalizing gait characteristics to women from groups of males or males and females can result in misconceptions, especially since studies done by several researchers (Buckalew, Barlow, Fischer, & Richards, 1985; Chao, Laughman, Schneider, & Stauffer, 1983; Williams, Cavanagh, & Ziff, 1987) have shown differences in stride characteristics between men and women.

Purpose

The purpose of this study was to examine the ground reaction forces and center of pressure patterns of a female distance runner. Specifically, the relative ground reaction forces and centers of pressure for shod and barefoot conditions were compared. A runner with asymptomatic gait was analyzed to increase understanding of normal parameters. The information gleaned from this study will add to the literature on asymptomatic subjects.

Delimitations

The subject in the study was a female distance runner training 35+ miles per week at an eight minute mile pace. The purpose of the study was to examine the center of pressure patterns under two conditions: barefoot and with shoes. Since it was not the purpose of this study to derive statistical norms of center of pressure during running, only one subject was used. While only data on the left foot were collected, symmetry was not assumed. The fact that the left foot was chosen for study was arbitrary. Due to unavoidable circumstances (computer changeovers), the initially proposed biodynamics study was not performed. Anthropometric data were gathered, and targeting and filming using high speed cinematographic procedures were obtained for the original biodynamic study. Reference to these aforementioned data, particularly on the Subject Information sheet (Appendix A), refer almost entirely to the biodynamic study. However, the kinematic and kinetic data and analysis programs are available from the author and author's advisor for future analysis.

Assumptions of the Study

The major assumption of this study was that the athlete did not alter her normal running pattern due to the experimental set-up. The subject was allowed as many practice runs as necessary before data were gathered, and she was required to land on the force platform with her left foot while maintaining a normal stride. A normal stride was defined as one in which the runner did not have to lengthen or shorten her stride to hit the plate and her whole foot contacted the plate. A trained observer watched the subject's stride and foot-force plate contact for each trial. In addition, feedback from the runner to the researcher was given after each trial. Trials for which the runner felt she needed to stretch to reach the plate or shortened her step to hit the plate were not analyzed. Finally in order to establish reliability in the trials chosen for analysis, the film data also was reviewed and used as a screening method. Of eight trials, three were unable to be transferred due to computer malfunction and/or they failed to meet the criteria for normal strides.

Chapter II

Review of the Literature

For hundreds of years social gatherings have included foot races, from the marathons of ancient Greece to the New York and Boston marathons run today. Running and racing are popular forms of recreational, therapeutic, and serious athletic activities. Biomechanics offers exercise science, physical therapy, engineering, osteopathy, and other related fields a technique to study and provide insight into the basic mechanism of movement. Although biomechanics draws on many diverse areas, it is a discipline in itself. Miller and Nelson (1976) defined this science as one which investigates the effects of internal and external forces upon living bodies. To review the literature for biomechanics one must go to journals of engineering, medical science, sport, and biomechanics.

This review of literature encompasses research findings of studies involving female subjects, ground reaction forces and center of pressure. The following chapter is separated into two parts. The first section reviews the history of exercise science investigations of ground reaction forces and female runners. Kinetic methods of three-dimensional gait analysis is the focus of the second section.

I. History

The history of scientific gait analysis begins with the development of photography. Although photographs have been around since the late Renaissance (15th century), photography was not used as a motion analysis tool until the 1800's. In 1878, Muybridge (1955) used a series of cameras set up with trip wires to film a running horse. This series of pictures was the beginning of cinematography. A Frenchman, Marey (1895), took Muybridge's idea further by using a single plate to record a series of exposures. These two men are credited with pioneering cinematography. Today, high speed cinematography enables scientists to gather movement information over very short time intervals.

A second major advance in motion analysis was the development of the force platform. The force platform is the basic tool involved in recording kinetic findings. Most of the investigations reporting kinetic data were performed within the last fifteen years because of the advancements in the development of force platforms and computer technology. Although many advances are recent, the study of gait may have begun with something as simple as examination of footprints in a smoothed garden plot. Researchers including Fenn (1930a, 1930b), Elftman (1939a, 1939b), and Manter (1938) conducted studies that were to become classics in the field of biomechanics. Their work in the 1930's formed the technological basis for the study of ground reaction forces today.

Ground reaction forces have been studied for over 50 years for both sprint and distance running. Measured with a force plate, ground reaction forces are the reactions of the ground to the force applied as a person moves in the superior-inferior, anterior-posterior, and medial-lateral directions and the moments about those primary axes. In 1930, Fenn (1930a, 1930b) pioneered kinematic and kinetic studies of sprint running utilizing a crude force plate. He matched vertical and anterior-posterior impulses to determine changes in mechanical energy. Conceptually, Fenn was one of the earliest investigators to provide a foundation for present day research. Another early investigator of gait was Elftman. In 1939, Elftman (1939a, 1939b) presented methods for calculating the rate of energy transfer across joint centers and rate of change of energy of the legs during walking. One year later, Elftman (1940) analyzed one running stride by utilizing free body diagrams and force-mass acceleration principles similar to those used later by Plagenhoef (1966, 1971), Dillman (1970), and Miller and Nelson (1976). Manter (1938) contributed a classic study that helped form the basis for modern day biomechanics. Manter examined muscle torques of a cat walking by using a combination of moving pictures and a platform that recorded force.

Ground reaction forces recorded by a force platform are useful as descriptive tools to analyze the support phase of running (Cavanagh & LaFortune, 1980; Dickinson et al., 1985; Hamill et al., 1983; Munro et al., 1987; Soutas-Little, Beavis, Verstraete, & Markus, 1987). Often the information gathered aids in improved understanding of the etiology of lower extremity injuries (Gudas, 1980; James, Bates & Osternig, 1978; Subotnick; 1977), improvement in shoe design (Bates, Osternig, Sawhill, & James, 1983; Cavanagh, 1980; Nigg, 1986; Nigg & Bahlsen, 1988; Nigg & Morlock, 1987), and assessment of nonpathological gait (Chao et al., 1983; Soutas-Little et al., 1987; Soutas-Little, Frederickson, Schwartz, & Soutas-Little 1987; Snow, 1990). For the current study, force platform data were gathered to obtain ground reaction forces and center of pressure for the foot.

Although ground reaction force investigations on adult male subjects were more common than those done with adult female subjects, generalizing the findings from males to females would appear to be inappropriate. In gait studies of walking and running, gender-related characteristics often were noted. Chao, Laughman, Schneider, and Stauffer (1983) presented three-dimensional data on walking and noted gender differences in temporal stride characteristics and ground reaction forces. However, age was not controlled for in this study, which contaminated the male/female comparison. Several researchers (Buckalew et al., 1985; Williams et al., 1987) demonstrated that differences existed in the mechanics between adult male and female runners. Williams et al. (1987) found that elite female marathoners "exhibit more hip flexion, greater angular velocities in hip flexion and extension, and longer stride lengths relative to leg length than do their male counterparts" (p. 117). Buckalew et al. (1985) showed that "women spend greater time in the support phase and less time in the nonsupport phase of running than men do" (p. 341). Gender related differences in running have also been observed in children as young as four and five years of age (Fortney, 1983). Even though the analysis was two-dimensional in nature, the differences in running shown in joint angles and angular velocity may extend into adulthood. Several additional studies involved groups of subjects consisting of both males and females (Bahlsen & Nigg, 1987; Cavanagh & LaFortune, 1980; Frederick & Hagy, 1986; Hamill et al., 1984; Rohrle, Scholten, Sigolotto, & Sollbuch, 1984). However, in their research, these investigators did not report any comparison between data on male and female subjects, nor did they mention the possibility of gender-related differences.

Although some comparison of temporal and positional characteristics of elite males and elite females has been performed (Buckalew et al., 1985; Williams et al., 1987), there is a need in the literature for comparing ground reaction forces and centers of pressure. In addition, three-dimensional analysis techniques have not been commonly used (Chao et al., 1983; Kinzel et al., 1972; Soutas-Little et al., 1987; Soutas-Little et al., 1987). A further problem with conclusions concerning the presence or absence of gender differences may be that most females studied were members of a higher skilled, elite population (Bates & Haven, 1973; Bates & Haven, 1974; Buckalew et al., 1985; Haven, 1977; Nelson, Brooks & Pike, 1977; Williams et al., 1987). Elite runners are a group that is unique when compared to "average" runners in terms of the frequency of workouts, speed, and other training factors. Due to emerging evidence of gender differences in mechanics of running and walking, mixed data may not be accurate for describing both males and females.

Though the investigations of Williams et al. (1987) and Buckalew et al. (1985) did compare elite male and elite female performance factors, neither measured ground reaction forces or center of pressure. No studies, with the exception of Soutas-Little et al. (1987), have examined ground reaction forces and center of pressure specifically for "average" females. Moreover, due to the recent technological advances in biomechanics, three-dimensional analysis techniques have yet to be commonly employed to analyze gait. The few exceptions include the work of Soutas-Little et al. (1988), Soutas-Little et al. (1987), Chao et al. (1983), Chao and Rim (1973), Snow (1990), and Verstraete (1988).

II. Kinetics

Cinematography provides descriptive data, but, since forces can not be calculated from position data, this kinematic method is not usually employed alone in the study of gait. A force platform is used commonly in conjunction with kinematic data to provide three-dimensional information on ground reaction forces and moments during the stance phase of running or walking. However, recently the force plate has been used in examining back pain (Johnson, 1990), and in attempting to determine normal ranges of gait (Snow, 1990; Soutas-Little, et al. 1988). Both the reaction of the ground to the force applied by the subject in the x, y, and z orthogonal directions and the moments about these axes are measured by the force platform. By using this information, the center of pressure can be calculated between the ground and the foot. Most of the past biomechanical literature involving gait and ground reaction forces dealt with two-dimensional analyses. Since the majority of motions associated with running occur in the sagittal plane, many researchers observed and analyzed motion occurring in this plane. Seminal studies in two dimensions analyzing gait in a sagittal plane were done by Elftman (1939a, 1939b) and Manter (1938). Elftman's research on walking was a planar description of motion and forces. His methods for calculating forces and moments of the lower limb during walking are still being used today. Manter (1938) was among the first to combine force plate data with cinematography successfully to analyze motion in the sagittal plane. Using the recorded motions and forces, he calculated muscle moments in the sagittal plane in the limbs of a walking cat.

In general it was thought that motion outside the sagittal plane during running and walking was negligible. However, research employing methodology to analyze moments in three dimensions has demonstrated otherwise. The three-dimensional forces and moments of the lower limb during a complete walking stride were calculated by Bresler and Frankel (1948). These researchers emphasized the importance of the nonsagittal components of the joint forces, such as the medial-lateral moment, in providing stability during stance, as well as their effect on the moments at the hip. Using similar methods for computation, Andriacchi and

Strickland's (1985) results agreed with Bresler and Frankel's (1948) analysis that all three components of a moment at a joint were important.

Two-dimensional investigations utilizing female distance runners and ground reaction forces are relatively few in number and those done in three-dimensions are even fewer. Generally, those studies that do exist tend to examine temporal factors such as stride length and percent time spent in the support phase (Bates & Haven, 1974; Buckalew et al., 1985; Nelson et al., 1977) and/or evaluate positional data and its derivative, velocity (Bates & Haven, 1974; Buckalew et al., 1985; Nelson et al., 1977; Ulibarri, 1974). Only one two-dimensional study discussed biomechanical force aspects of female runners. Williams et al. (1987) used ground reaction forces obtained from the force plate to study relative motion of the foot to the ground. Biomechanical variables included: footstrike patterns, peak forces during stance, and asymmetry of forces between right and left feet. Results of the study included vertical ground reaction forces of 3.3 times body weight for elite female distance runners and asymmetry expressed mainly in the mediolateral component of the stance phase.

One group of researchers did combine three-dimensional techniques and force data to observe female gait. Soutas-Little et al. (1987) presented a Dynamic Profile of Female Gait at the 1987 Biomechanics Symposium. The investigators utilized Grood and Suntay's (1983) joint coordinate system to obtain relative three-dimensional motions between the forefoot, rearfoot, thigh, and shank. Moments for the ankle, knee, hip, and the total support moment were also examined. The results indicated that the hip moment differed the most from person to person (Soutas-Little et al., 1987).

A few studies have examined center of pressure for runners and/or walkers (Cavanaugh & Lafortune, 1980; Munro et. al., 1987; Soutas-Little et al., 1987; Snow, 1990). However, with the exceptions of Snow (1990) and Soutas-Little et. al. (1987) center of pressure was used as a method of classifying footstrikes and was not the primary focus of the study. Snow (1990) analyzed a group of nine males and seven females walking and running in both bare feet and shoes. He compared resultant force and torque vectors, their positions and the paths of the intercepts with the force platform surface. Soutas-Little et al. (1987) also compared center of pressure between nonpathological runners and walkers. Her study was unique in that all 27 of the subjects were female and many aspects of gait were examined. Her findings demonstrated that the moment at the hip appeared to be the most sensitive to individual gait variations. The results of the study indicated that individual characteristics for gait could be obtained and that the ground reaction force and center of pressure data supported the existing data on women.

Chapter III

Experimental Methods

The contents of this chapter deal with the methods of data collection and analysis. The methods for data collection and analyses utilized were developed by researchers in the Department of Biomechanics at Michigan State University. The testing procedure for the runner consisted of a single filming session held at the Center for the Study of Human Performance in Erickson Hall at Michigan State University. Upon arrival, consent and subject information forms (Appendix A) were completed. The subject wore running shorts and top for the filming. The athlete was weighed to the nearest kilogram and after a warm-up period completed eight trial runs: four barefoot and four with shoes. Kinematic and kinetic data were collected for the left limb only.

The runner was given a 20-25 minute period to warm-up using her own regime of stretching and jogging. She was also given the opportunity to practice steps so as to strike the force plate with her whole foot using her natural running stride. As many practice runs as necessary were allowed to let the athlete feel comfortable striking the force plate. The runner was instructed to run at a pace comparable to what she used during a daily workout. Although a literature search revealed that asymmetries may exist between right and left limbs (Snow, 1990), only forces for the left limb were recorded and analyzed, and symmetry was not assumed. The left side was arbitrarily chosen for analysis. The purpose of the study was to examine the ground reaction forces and center of pressure patterns of a female runner.

Trial reliability was verified by initial screening on the site of data collection by experienced observers, the runner's confirmation that the stride "felt" normal, and by study of the film at a later date. A trial was considered acceptable if the following criteria were met: 1) the subject observed that the stride was comfortable; 2) the observers did not discard due to a lengthening or shortening of stride; and 3) the subject contacted the force platform with the entire foot. Of the eight trials three were discarded due to unnatural strides or equipment malfunction during transferring of the data.

Four trials each of running in bare feet and shoes were filmed. An AMTI OR-6 force dynamometer capable of recording at a rate of 1000 Hz was used to measure ground reaction forces during the stance phase of running. The force plate was level with the floor in a fifty foot runway. Ground reaction forces were recorded with respect to a frame of reference on the platform (Figure 1) for the Z, Y, and X forces (Figures 2, 3, and 4). The primary axis forces and the moments (torques) of these axes were recorded by an IBM 9000 dedicated computer used in conjunction with the force plate to provide information for center of pressure calculations. Data collected were stored on floppy disks for transfer to the Prime computer located in the Case Center for Computer Aided Design at Michigan State University for analysis. Ground reaction force (GRF) descriptors used in the current study included: the magnitude of the maximum vertical GRF load; the magnitude of the vertical GRF load at heelstrike; the anterior-posterior (A-P) curve crossover; and duration of the stance phase. Descriptors used to assess the center of pressure plots (RVF plots) included: the magnitude of the heelspike vectors; the medial-lateral shifts of the center of pressure path; the magnitude of these shifts; and the uniformity of the overall vector pattern.

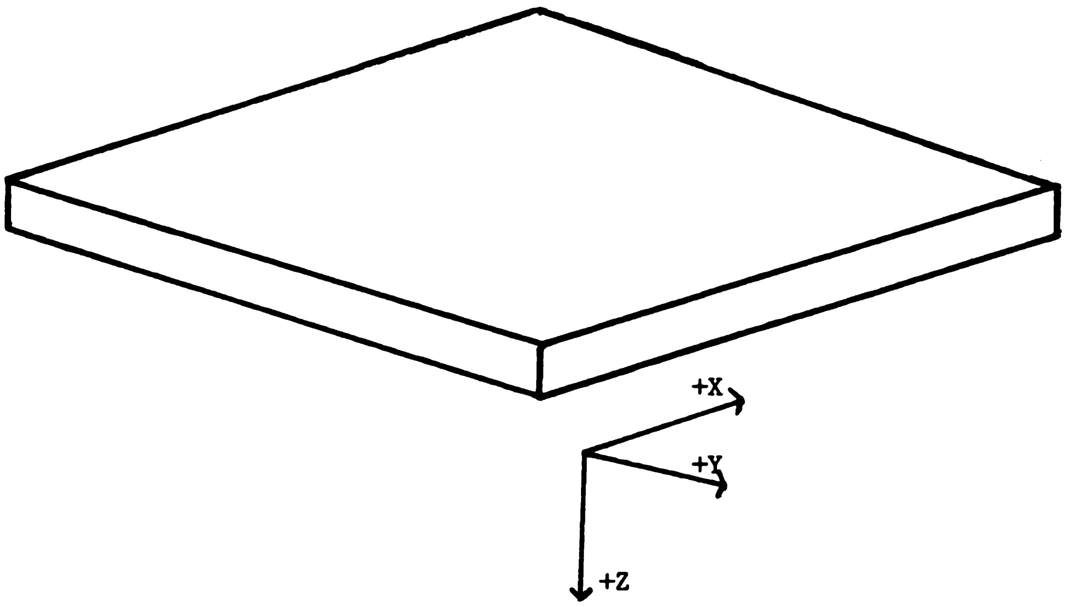

Figure 1 - Force Plate And Primary Vectors

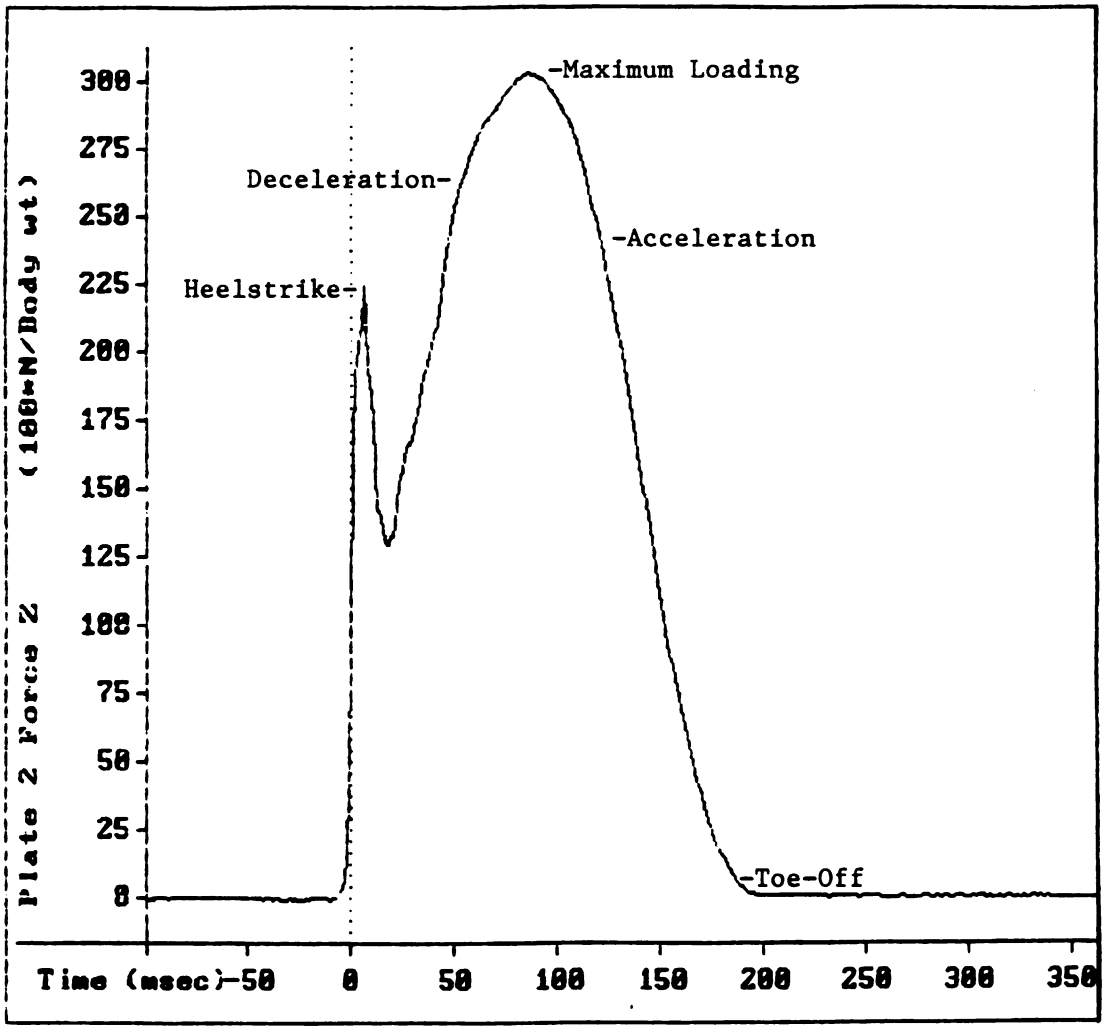

Figure 2 - Vertical Ground Reaction Force Graph (Z)

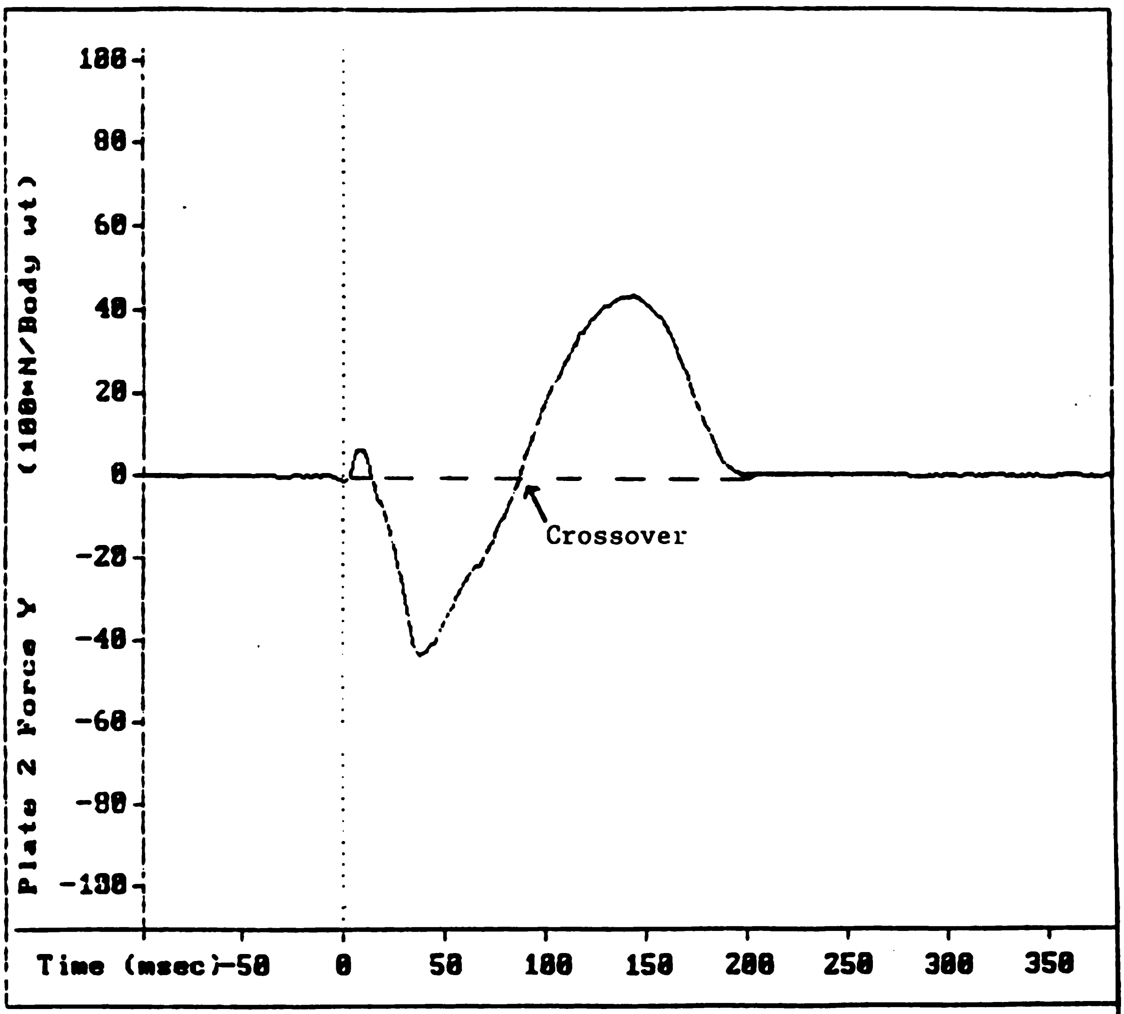

Figure 3 - Anterior(-)Posterior(+) Ground Reaction Forces (Y)

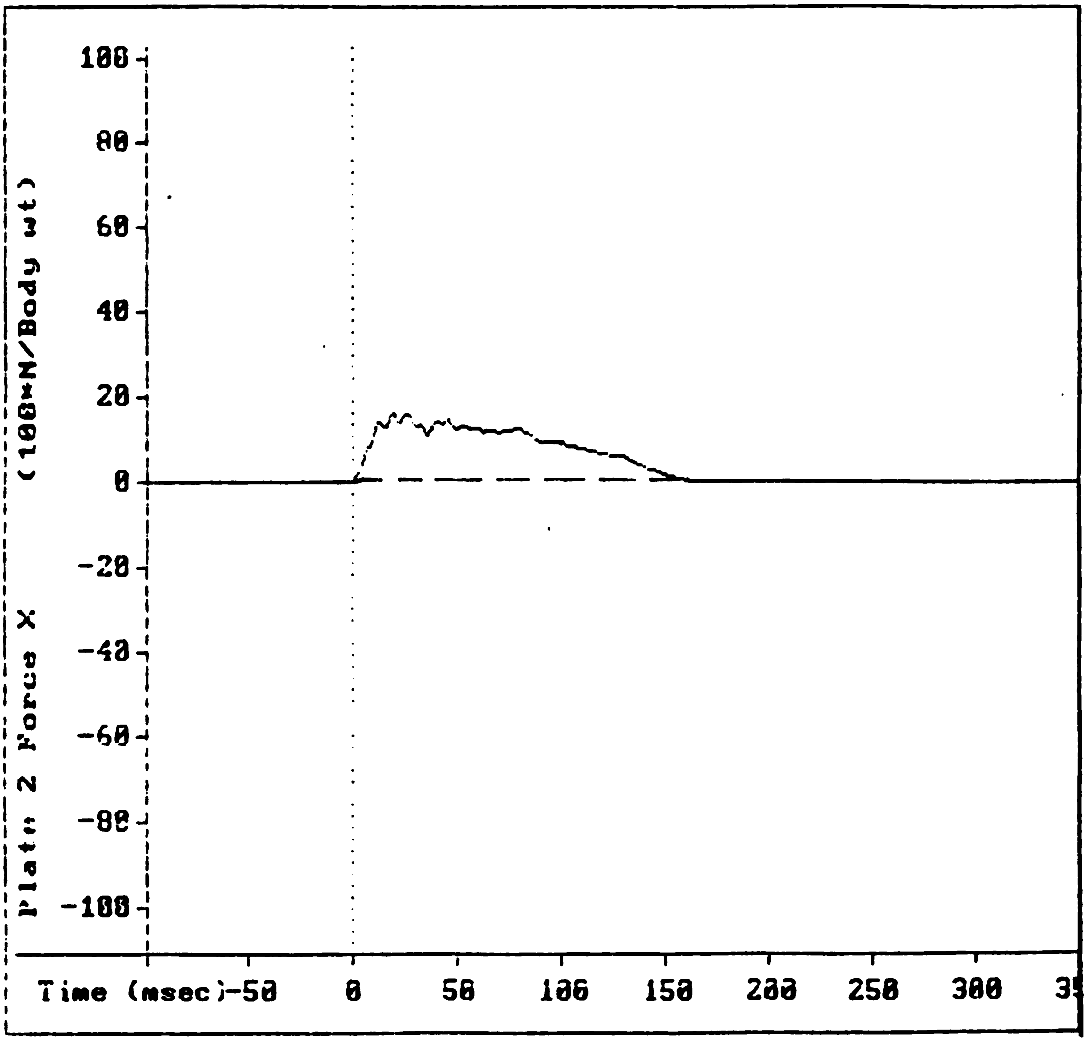

Figure 4 - Medial(+)Lateral(-) Ground Reaction Forces. (X)

The greatest amount of ground reaction force information can be obtained from the vertical force curve (Z curve) shown in Figure 2. The Z curve can be divided into several distinct phases: 1) heelstrike; 2) deceleration phase; 3) maximum loading; 4) propulsive phase; and 5) toe-off. Values for heelstrike loading and maximum loading, the time they occurred in milliseconds (ms), and the percent of stance in which they occurred can be derived from this curve. The anterior-posterior curve (Y curve) is shown in Figure 3. The point at which the A-P curve changes sign is referred to as crossover and it is an indication of velocity. If crossover is at 50% of the stance phase it indicates constant velocity. The subject in this study reached the A-P curve crossover at an average of 90 ms, which was 45% of stance and indicated that she accelerated during the propulsive phase. The medial-lateral curve (X curve) (Figure 4) characteristically has smaller relative magnitudes as compared to vertical (Z) and anterior-posterior (Y) curves. Another characteristic of the X curve is a tendency to be irregular in shape. The subject in this investigation displayed little medial-lateral motion throughout all five trials analyzed and, therefore, the M-L curves were only observed qualitatively for shape.

Besides ground reaction forces the force platform also collects three components of torque for ground reaction which define a resultant torque vector (RTV). The resultant torque vector (Shimba, 1984; Soutas-Little, 1987) can be separated into parallel and perpendicular components to the resultant force vector (RFV). The term for the resultant force vectors with a parallel torque component is wrench axis. The resultant vector intercept (RVI) path is the wrench axis intercept with the platform (Figure 5). The outcome of a combination of resultant vector intercepts

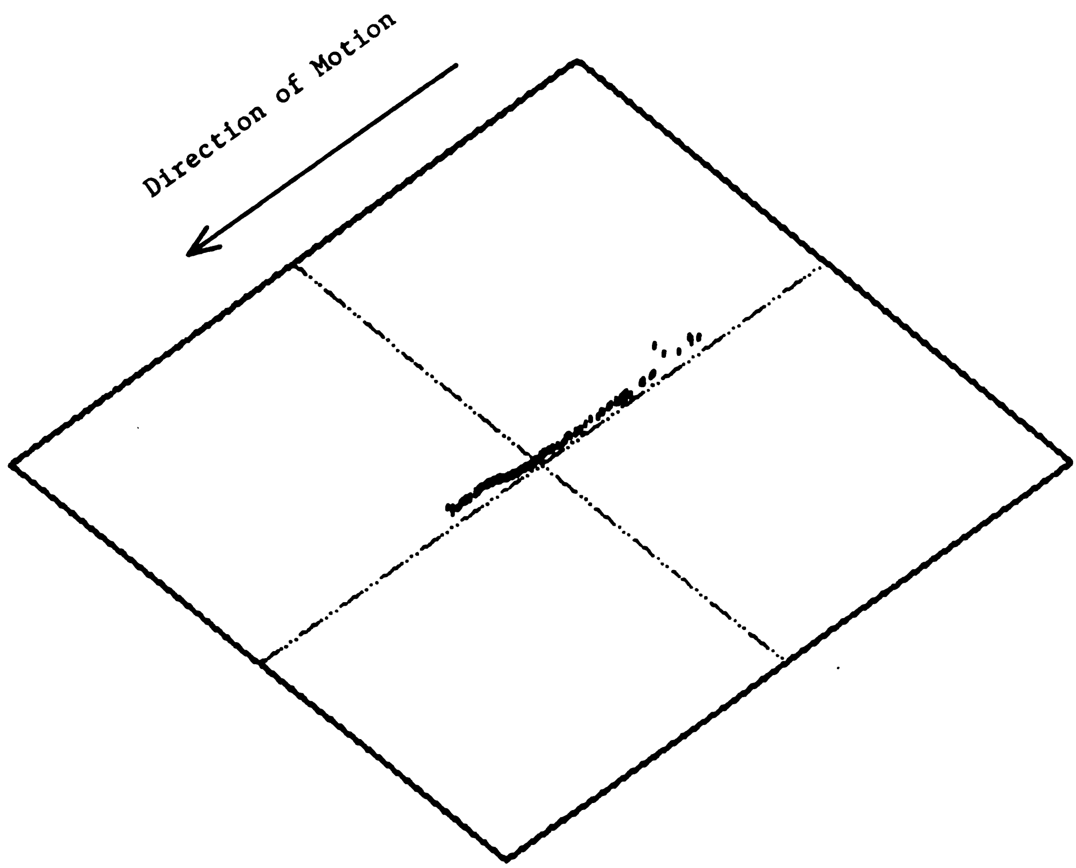

Figure 5 - Center of Pressure Path

(RVI) and resultant force vectors (RFV) is a resultant vector force (RVF) plot (Figure 6). These relationships are summarized in the following points. Mathematical descriptions can be found in Shimba (1984).

1. The combination of X, Y, and Z GRF yields the RFV (Resultant Force Vector).

2. The combination of torques about the X, Y, and Z axes yields the RTV (Resultant Torque Vector).

   Note - The RTV has components that are parallel and perpendicular to the RFV.

3. The combination of RFV and the parallel torque component of the RTV yields the Wrench Axis.

   Note - the intercept of the wrench axis and the plate is defined by the magnitude and direction of the torque component (RTV) that is perpendicular to the wrench axis.

4. Collective loci of the wrench axis intercepts with the force plate surface yields the Resultant Vector Intercept (RVI).

5. The combination of the RFV and the RVI yields the Resultant Vector Force (RVF).

Details that can be obtained from the resultant vector force plot, also known as the center of pressure plot, are related to the length and direction of the vectors. Length of the vector is a function of the magnitude of force, as the longer vectors indicate a greater magnitude of force than the shorter vectors. Direction is evidence of deceleration and acceleration. Vectors pointing backward in relation to the direction of the motion of the subject are a sign of deceleration. Vectors pointing forward in relation to the direction of the motion of the subject are a

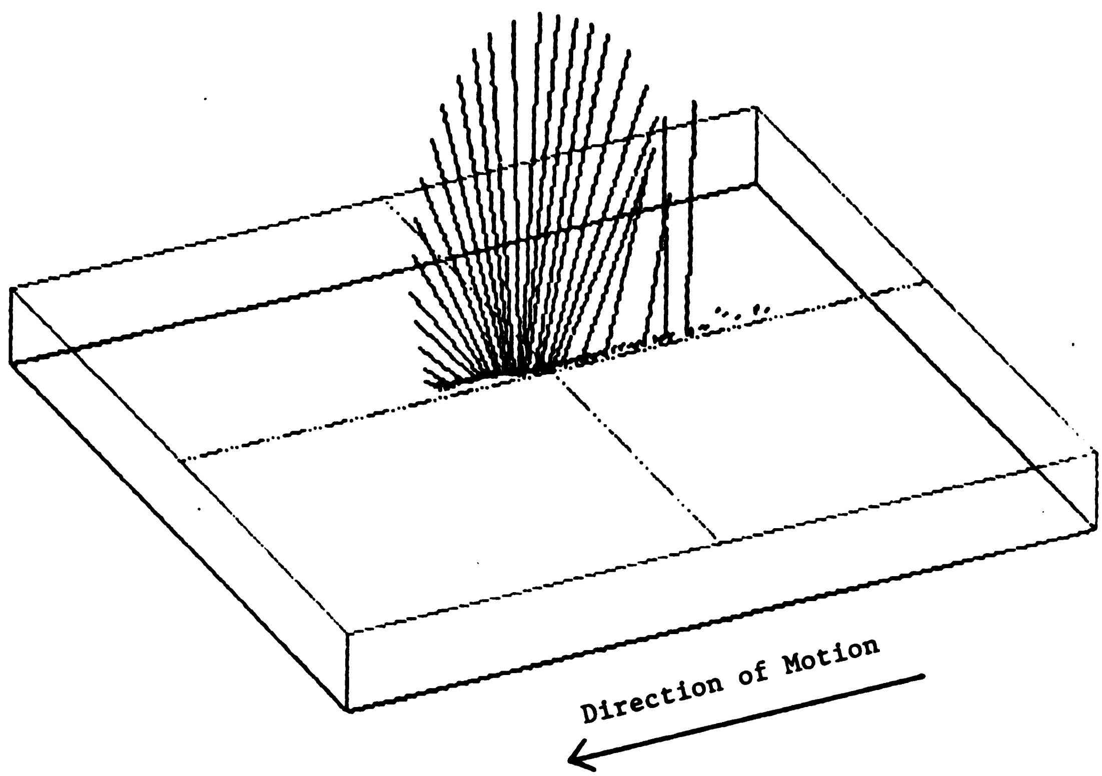

Figure 6 - Center Of Pressure Plot

sign of acceleration. Vector density of center of pressure plots was plotted by sampling at a constant rate of 7 ms for all five trials. When running the program to display the center of pressure, the scale factor for vector length and the view were held constant from trial to trial.

Chapter 4

Results

This chapter details the results of the analysis of the ground reaction forces and centers of pressure of an asymptomatic female distance runner. Comparisons are made both within and between barefoot and shod conditions. Particular attention is paid to heelstrike loading, maximum loading, A-P curve crossover, medial-lateral shifts, and percent stance.

I. Ground Reaction Forces

The force plate measures orthogonal forces in the vertical, the anterior-posterior (A-P), and the medial-lateral (M-L) directions. The vertical force curve or Z graph displays the loading, smaller initially, corresponding to heelstrike and reaching maximum loading around midstance (Figure 2). Average loading at heelstrike was 2.3 times the subject's body weight and reached 2.8 to 3.1 times body weight during the time the foot was on the force plate (Table 1). The A-P curve (Y graph) is shaped like an inverted sine curve (Figure 3). The point during midstance in which the sign of the curve changes is termed the A-P curve crossover. The M-L curve (X graph) tends to display relatively small magnitude changes, inconsistent signs, and irregular shape (Figure 4). The M-L graphs were observed qualitatively only for possible large differences from trial to trial.

Data from the present study on ground reaction descriptors for barefoot and shod running are presented in Table 1. The values of the results between trials are fairly close. For example, for bare feet the total time the foot was on the force plate ranges from 194-200

TABLE 1

LOADINGS, % STANCE TIME, AND DURATIONS OF LOADINGS FOR BAREFOOT AND SHOD TRIALS

Trial	Heelstrike (times BW)	H.S. % Stance (%)	Maximum Vertical Load (times BW)	Max Load % Stance (%)	Stride Duration (ms)	A-P Curve Crossover (ms)	Crossover % Stance (%)
1	2.3	3.2	3.1	45.1	194	87	44.8
2	2.2	3.1	3.0	41.7	200	93	46.5
3	2.3	3.2	3.1	44.2	198	90	45.5
Barefoot							
Mean	2.25	3.13	3.01	43.7	197	90	45.6
Range	2.2-2.3	3.1-3.2	2.94-3.05	41.7-45.1	194-200	87-93	44.8-46.5
4	2.3	6.0	2.8	44.7	210	90	42.9
5	2.5	6.3	3.0	37.5	200	94	47.0
Shod							
Mean	2.21	6.15	2.89	41.1	205	92	44.95
Range	1.93-2.5	6.0-6.3	2.83-2.95	37.5-44.7	200-210	90-94	42.9-47.0

milliseconds (ms). The range of time spent in stance for trials with shoes was 200-210 ms, slightly longer than the barefoot trials. The average magnitude of force at heelstrike for the barefoot trials was 2.3 times the subject's body weight (BW) and the maximum loading for barefeet reached 3.0 times body weight at its highest point. The average values for shod trials were slightly lower at 2.2 times body weight for the magnitude of forces at heelstrike and increasing to 2.89 times body weight at maximum loading.

The point of crossover of the anterior-posterior force curve gave information relating to velocity. If crossover is at exactly 50% of the stance time, it is an indication of constant velocity during the time that the foot is on the force plate. This subject was consistent in that the point of crossover was at less than 50% of stance for every trial, indicating that the subject accelerated during the second half of stance, also known as the propulsive phase.

II. Barefoot Trials

During the first of the three trials with bare feet the subject scuffed the force plate with her heel before heelstrike. The heelstrike occurred at 6.2 ms, 3.2% of the total time the foot was on the force plate (Table 1) and reached a magnitude of 2.3 times the subjects' body weight. After heelstrike the subject moved off her heel and began to decelerate. A-P crossover occurred at 87 ms, 44.8% of stance. At this point the subject began to accelerate. A maximum loading of 3.1 times body weight was reached at 45.1% of stance.

The center of pressure path was found to be fairly straight across the length of her foot, shifting slightly medially for toe-off (Figure 7).

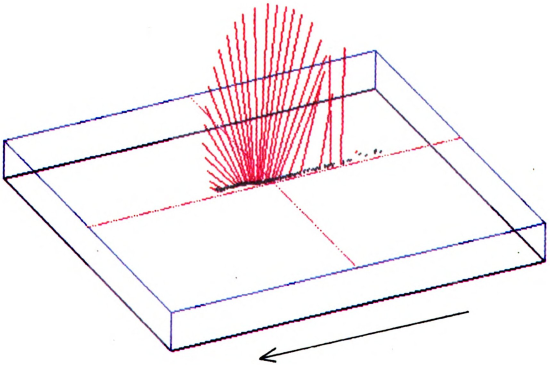

Figure 7 - Center Of Pressure Plot Trial 1

The overall pattern of vectors was a fan shape with evenly spaced vectors indicating a fairly uniform movement across the plate.

For the second trial, the subject again scuffed the force plate with her heel before heelstrike. The heelstrike was 3.1% of the total time the foot was on the force plate, occurring at 6.25 ms after which she began to decelerate. The loading at heelstrike reached 2.2 times the subject's body weight, a similar value to Trial 1. At 93 ms, 46.5% of stance (Table 1), the subject began an acceleration which continued throughout the latter half of the stance phase. Prior to acceleration, at 41.7% of the stance phase, a maximum vertical load of 3.0 times body weight was attained.

The center of pressure path was in a relatively straight line across the length of her foot, again shifting slightly medially for toe-off (Figure 8). Once more the overall pattern of vectors was evenly spaced, evidence of a fairly uniform movement across the force plate.

The third barefoot trial did not deviate from Trial 1 and Trial 2. Once again the heel was scuffed against the force plate before heelstrike (Figure 9). There was a quick heelstrike compared to the total time the subject spent in the stance phase, 6.2 ms or 3.2% of the total time the foot was on the force plate (Table 1). Heelstrike loading achieved a value of 2.3 times the subject's body weight. She then moved off her heel and decelerated until 90 ms, 45.5% of stance, at which point the propulsive phase began. Just prior to the propulsive phase a maximum vertical load of 3.1 times body weight was reached.

The center of pressure path was in a fairly straight line during trial three which was in agreement with the first two trials. In Trial 3 there was some slight movement laterally of the center of pressure path

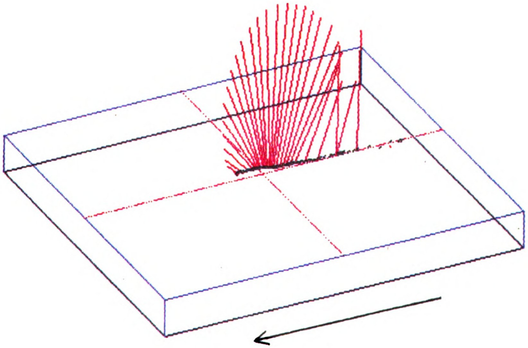

Figure 8 - Center of Pressure Plot Trial 2

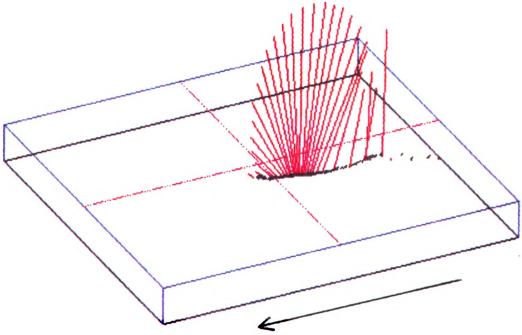

Figure 9 - Center Of Pressure Plot Trial 3

with a medial shift once again at toe-off. The overall pattern of spacing for the vectors, an indication of velocity, was uniform, another consistent trait of this subject.

III. Shod Trials

In Trial 4 and Trial 5 the subject wore her personal running shoes and there were no built-in wedges or special orthotics that would cause a deviation in the center of pressure path. The subject scuffed the force plate with the heel of her shoe before actual heelstrike in Trial 4 (Figure 10). The heel scuff was of greater force than the scuffs from the three barefoot trials (Figures 7, 8, and 9). After a quick heelstrike, only 12.5 ms or 6% of the total time her foot was on the force plate (Table 1), she moved off her heel and began to decelerate. At 90 ms, 42.9% of the stance phase, she began accelerating and continued throughout the propulsive phase. Heelstrike loading was 2.3 times the subject's body weight. The maximum vertical load was 2.8 times body weight, slightly less than that of the barefoot trials.

The center of pressure path was in a nearly straight line across the length of her foot with a slight overall drift in a medial direction (Figure 10). The center of pressure path traveled laterally for toe-off. As in the barefoot trials the overall pattern of vectors was uniformly spaced indicating uniform movement across the force plate.

Before heelstrike in Trial 5, similar to Trial 4, the subject scuffed the force plate with the heel of her shoe with greater force (Figures 10 and 11) than in the barefoot trials. The heelstrike for Trial 5 was the slowest of the five trials, lasting 12.5 ms, 6.3% of total stance time (Table 1) and achieved a value of 2.5 times the subject's body

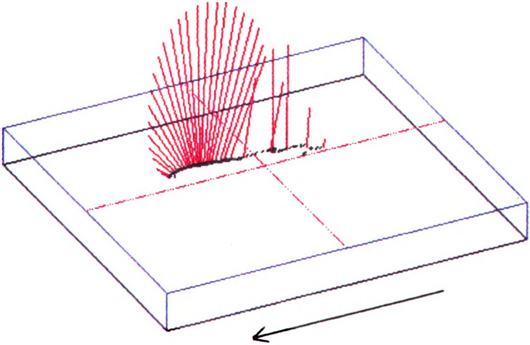

Figure 10 - Center Of Pressure Plot Trial 4

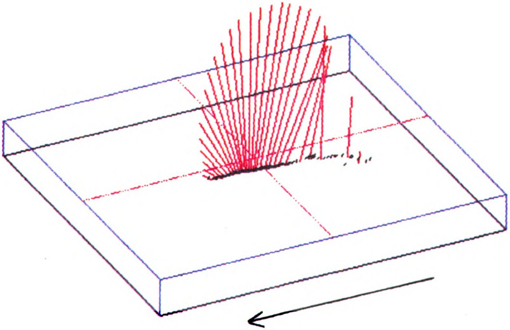

Figure 11 - Center Of Pressure Plot Trial 5

weight. Then she moved off her heel and began to decelerate. A-P crossover occurred at 94 ms, 47% of the stance phase, then the subject began to accelerate. Maximum vertical load reached 3.0 times body weight at 37.5% of the stance phase. During this fifth trial, as in the previous four, the center of pressure path was in a relatively straight line across the length of the subject's foot, ending with a slight drift medially at toe-off (Figure 11). Consistent with trials one through four, the spacing of the vectors was fairly equal, signifying uniform movement across the plate.

Chapter 5

Discussion and Conclusions

In the study of human movement the product of the system is analyzed and deductions made as to the cause of the movement. Accordingly, insufficient knowledge of average movement parameters for males and females has made defining anthropomorphic and physiologic variability difficult. The key to understanding gait pathologies is to establish a pool of data demonstrating a range of "normal" function. This investigation was designed to add to the small amount of existing knowledge of normative functioning for an asymptomatic skilled female distance runner. Three barefoot trials and two trials with shoes were chosen for examination of the center of pressure and ground reaction forces. This chapter is a discussion of the similarities and differences demonstrated from trial to trial and between shod and barefoot conditions for a female distance runner.

The barefoot trials demonstrated a consistent pattern as the differences displayed from trial to trial were extremely small (Figures 7, 8, 9, and Table 1). In fact, Trial 1 and Trial 2 were difficult to distinguish from one another and the differences noted here were between the first two trials and Trial 3. The third trial had a slightly higher heel spike in comparison to the first two trials. Trial 3 also displayed a center of pressure path that shifted laterally and then medially for toe-off, while the first two trials showed no lateral movement. Similarities between all three trials included: 1) scuffing the heel before heelstrike; 2) a quick heelstrike (ranging from 6.21 ms-6.25 ms, or 3.1%-3.2% of the total time the foot was on the plate); 3) magnitude of heelstrike ranged from 2.2-2.3 times B.W. and maximum vertical load ranged from 2.94-3.05 times B.W.; 4) a center of pressure path that moved in a relatively straight path across the length of the foot; and 5) a slight medial shift at toe-off.

In both shod trials, the overall pattern was much the same with genuinely small differences displayed. The center of pressure path was a predominantly straight line across the length of the foot in each trial with a only slight difference before toe-off. The center of pressure drifted in a medial direction in trial five prior to toe-off (Figure 11), while in Trial 4 (Figure 10) the center of pressure moved medially slightly and then laterally before toe-off. Trial 4 also appeared to have had a more definite heelstrike than Trial 5, with the heelstrike in five being slightly slower (Table 1). Similarities included: 1) scuffing the heel before heelstrike; 2) a quick heelstrike (12.5 ms or 6.0-6.3% of the total stance time); 3) magnitude of heelstrike ranged from 1.93-2.5 times B.W. and maximum vertical load ranged from 2.83-2.95 times B.W.; 4) uniform velocity; and 5) a center of pressure that moved in a predominately straight path across the length of the foot.

Once again, the patterns displayed were very consistent when trials with shoes were compared to trials with bare feet. The differences from trial to trial were small where they existed at all. One apparent difference was the magnitude of loading for heelstrike for the shod trials which were, 2.3 times B.W. compared to 2.2 times B.W. in the barefoot trials. This indicated the subject landed on the force plate with slightly more force when shod. This finding is consistent with previous work that has compared barefoot running and running with shoes (Snow, 1990). Perhaps this greater magnitude at heelstrike was due to the running shoe's greater area for landing and the shoe material, both of which allow more force to be dissipated through the shoe, as opposed to striking the heel directly and having the force dissipated through the foot initially. Although the heelstrikes were very quick, ranging from 3.1%-3.2% of time spent in stance in the barefoot trials one through three, the heelstrikes were slower in the trials with shoes than in the barefoot trials, 6.0%-6.3% of stance (Table 1). Trial 4 and Trial 5 (shod trials) displayed a small amount of drifting in a medial direction at or near toe-off even though the center of pressure paths were fairly straight across the foot (Figures 10 and 11). Also, in two of the three barefoot trials (Figures 7 and 8), the center of pressure path definitely traveled in a predominantly straight line and then moved in a medial direction nearing toe-off. As the exception to all five trials, Trial 4 did show a movement in the lateral direction at toe-off (Figure 10). Similarities between shod and barefoot trials included: 1) the scuffing or dragging of the heel before heelstrike; 2) a quick heelstrike in terms of total milliseconds of time the foot was on the force plate; 3) the loading for heelstrike, although occurring at a slightly later percent of the stance phase in the shod trials than barefoot trials, ranged from 2.2-2.5 for the five trials; 4) maximum vertical loading was similar for both conditions with an average of 3.01 for barefeet and 2.89 for shod; 5) a straight path for the center of pressure; 6) medial movement at toe-off; and 7) uniform movement as evidenced by the regularly spaced vector patterns displayed.

Quantitative analysis of ground reaction forces has served as the subject of several research endeavors (Bates, Osternig, Sawhill & Hamill, 1983; Hamill et al., 1984; Munro et al., 1987). However, in this study as in Snow's (1990) thesis, the method of data evaluation was qualitative.

Snow compiled data for a normal male and female population, comparing right and left symmetry of ground reaction forces and center of pressure for running and walking. In light of Snow's data the subject in this study fell within the range for normal gait patterns for females. Overall, the center of pressure was very consistent from trial to trial and between shod and barefoot trials. Very little distinction could be made between the individual trials and grouped data. The subject demonstrated a quick heelstrike compared to the total amount of time spent in the stance phase and a fairly linear path for the center of pressure with a small amount of motion medially (in general) at toe-off. Her overall stride appeared to have been rapid and very smooth with an increase in velocity in the propulsive phase.

Insufficient knowledge of average movement for males and females makes comprehending pathologies difficult. Accurate knowledge of motion can yield information that will improve current methods of supporting the foot and replacement for malfunctioning joints. It can also lead to the improvement of rehabilitative exercises for diseased or injured joints (Kinzel et al., 1972). Attainment of this knowledge may demand separate analysis of men and women due to possible differences in gait as suggested by the results of several studies (Bucklew et al., 1985; Chao et al., 1983; Fortney, 1983; Williams et al., 1987).

Further analysis of nonpathological dynamic gait for females could include biodynamic analysis, which includes both the kinetics (forces) and kinematics (displacements, velocities, and accelerations) of motion. In a biodynamic analysis, moments of force can be calculated using the inverse dynamics approach to solving the problem at various joints (Verstraete, 1988). Understanding gait problems depends upon establishing a pool of data demonstrating asymptomatic function. It is this author's hope to add to work begun by Soutas-Little (1987) on analyzing dynamic gait patterns for asymptomatic females.

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APPENDIX A

APPENDIX A

Subject Information

Date: 4-20-89 Time: 2:00 p.m.

Subject No.: 1 Gender: female

Physical Information

Age: 25 years

Height: 5 ft. 3 in.

Weight: 116.5 lbs. 518.3 N

Shoe size: 8

Shoe style (company and name): ASICS - Lady Gel

Orthotics: No X Yes____
If yes, please describe on the reverse side (prescription/nonprescription, full or half foot, reason for use, how many years...).

Recent injuries (last 2 years): No X Yes____
If yes, please describe as fully as possible on the reverse side.

Running History

How long have you been running? 8 years

How many days per week do you run? 6 days

Approximate mileage run per week 35-45 miles

Do you currently compete in races? No____ Yes X
If yes, what distance(s)? 5K - 10K - Marathon

Did you compete in High School? No____ Yes X
If yes, describe: Cross Country X Track____ Other____

Average minutes per mile for your training pace: 8 min./mile

APPENDIX A

ANTHROPOMETRIC MEASURES

518.3 Weight (N)
1.6 Height (M)
22.4 % Body Fat

7 mm	Subscapular
11 mm	Suprailiac
11 mm	Triceps
5 mm	Biceps

23.6 cm	Foot Length	Tip of toe II to most post. pt. of calc. // to floor
3.5 cm	Heel Width	Width at level of target B // to floor
8.7 cm	Foot Width	Head of meta. I to head of meta. V
6.0 cm	Sphyrion Height	Tip of med. malleolus to floor
7.0 cm	Ankle Width	Width at target F // to floor
42.5 cm	Shank Length	From target I to target F
11.5 cm	Knee Width	Width at level of target I
11.7 cm	Condyle Width	Width at level of target J
75.0 cm	Thigh Length	From target M to target I
50.0 cm	Thigh Circumference	Circumf. at level of gluteal furrow
26.1 cm	ASIS-ASIS Distance	From right to left ASIS
81.5 cm	Limb Length	From target M to Floor

SUBJECT # 1