AN ABSTRACT OF THE THESIS OF

Dörte G. Engel for the degree of Master of Science in Apparel, Interiors, Housing and Merchandising presented on March 18, 1996. Title: A Comparison of Rearfoot Stability in three Women's Shoe Styles with Different Heel Dimensions.

Abstract approved: ________________________________

Nancy O. Bryant

The sports shoe industry has recognized the influence of shoe design on the biomechanics of walking and running. However, in the dress shoe industry, these influences have received little attention. Whereas rearfoot stability has been studied extensively in running shoes, few studies of women's high-heeled shoes have included rearfoot stability.

Recent studies which investigated rearfoot stability in high-heeled shoes (Ebbeling et al., 1994; Hontalas and Williams, 1995; and Snow and Williams, 1994) did not test the influence of different heel dimensions. The purpose of this study was to compare rearfoot stability in three women's shoe styles with different heel dimensions: a flat shoe, a high narrow-heeled shoe, and a high broad-heeled shoe. It was expected that the high narrow-heeled shoe would be least stable, the flat shoe the most stable with the high broad-heeled shoe falling in-between.

Women from the local business community were recruited as subjects (n=28). Their mean age was 37.5 (SD = 9.5), height 64.5 inches [164 cm] (SD = 2.6 inches [6.7cm]), weight 146.5 lbs [66.5 kg] (SD = 25.3 lbs [11.5 kg]), and they had worn high heels for at least 16-24 hours per week for the past year. Classic narrow toe style shoes of similar
construction (with exception of the heel) were used. The flat shoe was < 3/8 inches [1cm] in heel height, and the high heels were both 2.5 inches [6.4 cm] high. The ground-contact area of the narrow heel was 1/6 that of the broad heel (= 1/4 inches² [.5 cm²] and 1.3 inches² [3.5 cm²]). Three-dimensional kinematic data of subjects walking on a treadmill were collected using the Qualisys MacReflex System. The following parameters were measured: maximum pronation, pronation at heel strike, time to maximum pronation, stance time, and range of pronation (using maximum pronation minus pronation at heel strike). Subjects completed an informed consent form, were fitted for the correct shoe size, practiced walking on the treadmill, and underwent a clinical assessment.

Reflective markers were placed on the subject’s lower leg and the shoe. Data were collected with subjects walking at 2 miles/hour [0.88 m/s]. The shoes were presented in a randomized block order. Each subject walked on the treadmill in each shoe style for ten minutes while data focusing on the left leg and foot were recorded.

Five full gait cycles were analyzed. To calculate the rearfoot angles, the leg angle and the foot angle were calculated first. The rearfoot angle was calculated using the degree of toeout (calculated from the toe marker) to gain an angle projected onto the plane rotated about the leg by the amount of toeout for every data frame. The average for all five gait cycles of each dependent variable studied for each subject was used for statistical analysis. The statistical approach used was a repeated measures ANOVA, a post hoc analysis, and a correlation matrix to compare the kinematic and questionnaire data.

There was a significant difference in rearfoot stability between the high narrow-heeled shoe and the high broad-heeled shoe for both maximum pronation and pronation at heel strike. But, there was no difference between these values for the high narrow-heeled shoe and the flat shoe. Both showed a maximum angle three degrees larger than the high broad-heeled shoe (= 12 vs. 9 degrees). Significant differences existed between the range of rearfoot motion for all three shoe styles. Range of rearfoot motion was largest for the high
narrow-heeled shoe (7 degrees, SD = 3.3) and least for the flat shoe (4 degrees, SD = 2.4) with the values for the high broad-heeled shoe (6 degrees, SD = 2.4) falling in-between. No significant differences between stance times or time to maximum pronation were found.

For the questionnaire, the results showed that subjects tended to wear a whole shoe size larger in fashion shoes (narrow toe box) than their measurements with a Brannock® device would suggest. There was no significant difference between the sizes worn for any of the three shoe styles investigated. Older subjects tended to own more high-heeled shoes and wear them more often and longer than younger subjects. This may be due to consumer trends. When the older women entered the job market it was expected of them to wear high heels as part of their business attire. Younger women are experiencing much more relaxed rules. There was no strong correlation between any of the questionnaire results and the kinematic data.

This study indicated that increasing the heel surface of a high-heeled shoe significantly aids in reducing rearfoot range of motion. Surprisingly, maximum pronation angle and pronation angle at heel strike did not follow the same pattern. The question that arises from these data is whether the maximum pronation angle is the best way to compare stability in shoes. Perhaps range of rearfoot motion is a better representation of true rearfoot stability. Further studies could investigate the relationship between rearfoot stability and heel dimensions in women’s shoes using a wider range of heel dimensions and possibly varying the heel materials.
A COMPARISON OF REARFOOT STABILITY IN THREE WOMEN’S SHOE STYLES
WITH DIFFERENT HEEL DIMENSIONS

by

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A COMPARISON OF REARFOOT STABILITY IN THREE WOMEN’S SHOE STYLES WITH DIFFERENT HEEL DIMENSIONS

CHAPTER I

INTRODUCTION

Statement of the Problem

Feet are the foundation of the human body and express the spirit of a person. "Good gait can subtract years from one's appearance by its spring, its stride, its rhythm, its ease" (Roberts, 1975, p. 1). Being mobile is closely connected to one's power and self-esteem or lack thereof, something which is often alluded to in popular expressions. Expressions such as 'being quick on your toes', 'standing tall', 'standing on firm ground', 'barefoot and pregnant' and 'letting your feet do the talking' are only some of the ways in which language symbolizes the importance of feet.

In Western culture, feet are usually covered with shoes for most of the day and most of the year. However, shoes, which are one of today's most important fashion accessories, cause discomfort for many of their wearers. For women, high heels especially cause discomfort and pain. For this study, high heels refer to shoes that elevate the heel of the foot at least one inch higher than the ball of the foot.

According to a recent study, only one percent of the American population wears shoes which fit properly (Tedeshi, 1991). Women have a tendency to wear shoes that are too short and too narrow. In a survey at the University of Southern California about 80% of women surveyed said they constantly experienced some foot pain (McAllister, 1991).

Many of the problems associated with aching feet are due to footwear. Many people are not aware that they have non-identical feet and have often not been measured for correct
shoe size in many years. Elizabeth Roberts, a podiatrist from New York City is especially outspoken in her opinion of shoe fashions:

I certainly hold no belief for shoe styling and for shoe merchandising. Shoe styles, particularly women's, change seasonally, but feet don't. Shoes are sold in pairs, but no one has a pair of feet. One foot is always larger than the other. Your two feet are no more identical than the two sides of your face. If the consumer's health were the chief consideration, shoes would be sold as right shoes and left shoes. This, however, would lead to additional inventory problems that apparently no manufacturer or merchant is willing to take upon himself (1975, pp. 129-130).

These are strong words for an industry providing such an important apparel item. Shoes used to be sold by trained personnel (Glen, 1948). Today, a shoe sales person needs only to be able to find the correct size in the stock room. The lack of training provided to salespersons is not the only reason for people's discomfort with shoes. As William Rossi (1988, p. 247), an expert in shoe merchandising and the author of many books and articles on the topic of shoes, stated: "Give the product a reason for being and you give the sales person a reason for selling and the customer a reason for buying." But the problem may be more complicated than just the availability of comfortable footwear.

Unable to find a comfortable dress shoe in the 1980s and into the 1990s, women as well as men often resorted to buying athletic shoes for everyday use. Only 14% of men's athletic shoes and only 8% of women's athletic shoes sold in 1990 were actually used to participate in sports activities. Nearly 70% of men's and 65% of women's athletic shoes were worn for everyday street wear, to work or to school (Silverman, 1991b). These figures indicate a possibly neglected niche in manufacturing comfortable women's dress shoes and especially high heels.

Women's high-heeled shoes pose a great problem for general foot health and posture. Many popular women's magazines have had articles on shoes in the past few years, many of them focusing on the drawbacks of high heels (Fellingham, 1991; J. M., 1992; Sandmaier, 1991; Sweet, 1992). Ellen Trevor (1994, p. 49), a writer for Walking
Magazine, warned readers to "beware of high heels. Every inch of heel height increases the force on the ball of your foot by 25% and raises your chances for foot problems." Lee Ann Broussard (1994), a writer for the Oregonian, recommended "women should avoid wearing high heels whenever possible." Even Barbra Streisand admitted she gave her farewell tour in 1994 because "[On stage] you have to wear high heels. My feet get cramps!" But regardless of complaints, "a third of the women [in a recent survey] said they wear high heels despite pain and potential foot damage" (1994, Maybe..., p. E2).

Women's complaints about achy feet have also been reflected in recent advertising promotions. A Liz Claiborne shoe advertisement stated: "The more a woman has to be on her toes, the less you see her in 4" heels," accompanied by a picture showing a pair of comfortable looking flat string mules (Glamour, 1992). An Easy Spirit® advertisement showed a white, life size sneaker under a small red pump with the caption: "How'd they ever get a sneaker in those slender little pumps?" (Working Woman, 1992) University Designs® showed a Barbie-like doll with four differently styled low-heeled casual shoes and the caption: "Until now, women's shoes weren't anatomically correct either" (Harper's Bazaar, 1992). This further shows that the concept of comfort is very important to some consumers. Even Birkenstock® compared its sandal foot product to fashion footwear in the Spring/Summer 1992 catalog by showing the bones of a cramped foot inside a women's high-heeled shoe and a view of the bones in a relaxed, comfortable foot inside a Birkenstock® sandal.

The apparent demand for more comfortable shoes has not fallen entirely on deaf ears in the fashion footwear industry. The shoe industry, just like the car industry, has recognized women as a market segment with discriminating, knowledgeable and value-conscious buying habits and a reasonable amount of available cash. Comfort pump companies such as Soft Spots®, Easy Spirit®, and Naturalizer® have been selling their comfortable low-heeled shoes to women and are doing very well according to a merchandise manager for
women's shoes at Nordstrom's (Fellingham, 1991). Shoe manufacturer Nine West's Clehane was quoted as saying "women want to have the same freedom with heel heights that they do with skirt lengths" (J. M., 1992, p. 180).

Dick Silverman (1994) went a step further in stating that "the footwear industry is undergoing one of the most fundamental changes it has experienced in generations." He quoted Gerald Celente, the director of the Trends Research Institute in Rhinebeck, New York as saying that "...by the year 2005, what used to be common office apparel — ties, suits, high heels — will only be used for ceremonial purposes, when people have to 'look the job,'..." (p. 25). If this trend indeed develops into reality, it will not only continue to drive the demand for athletic and casual shoes but also will increase the amount of comfort women will expect when they buy high-heeled shoes. Of course, nobody can predict the future, but if the last 150 years are any indication, high heels will continue to play a part in fashion for some time. According to the Knight-Ridder News Service, designers were trying hard to reverse the fashion for outdoor inspired footwear. Four-inch stilettos were frequently seen on the fashion runway for the fall 1994 season, a trend that continued in 1995. But Denise Cowie (1994, L19) was quick to point out that "no longer does anybody say this is 'the' shoe or 'the' skirt length."

The shoes offered by today's comfort shoe companies do not look recognizably different from other fashionable mid-to-high-heeled shoes in the moderate price range. The claims made about their supposedly greater comfort have not been substantiated with clinical findings but are usually proven by using supportive statements made by well-known figures considered authorities on the topic of shoes. A local Birkenstock store enlisted the help of a podiatrist to write an informational article for their information sheet for customers (Footwise, 1992). Similarly, high-heeled shoe companies often draw on authoritative celebrities to plead their case. In an article about shoes in the German
magazine *Stern*, British shoe designer Paul Lennard was enlisted to praise the current improved manufacturing techniques for high-heeled shoes (Neumann, 1993).

Justification of the Study

Although a number of empirical studies on the effects of high-heeled shoes have been published since the 1960s, there are still many questions to be answered. Fashion footwear constitutes an important part of the attire of many professional women. Since many businesses require or expect female employees to wear dress shoes, which often infers high heels, there is a great need to learn more about the effects of this type of shoe on the feet and body. This is especially important in order to improve the structural design of high heels.

Wearing uncomfortable shoes affects not only the feet themselves but many other parts of the body as well. Shoes may have a major affect on the alignment of the body and increase or cause damage to the back, knees, and ankles (Soames and Evans, 1987). Since dress shoes are bought to fit snugly, they often cause skin irritations, such as corns and calluses, hot or sweaty feet, fungus or ingrown toenails. Pronation (inward rotation of the foot) and supination (outward rotation of the foot) are also potential problems. About 95% of the population exhibits a varus foot type (a tendency to pronate or roll inward from the ankle), and 4% shows valgus feet (a tendency to supinate or roll outward from the ankle), according to Dr. Louis C. Talarico Jr. who has conducted 20 years of research on feet in Lewiston, Maine (Tedeshi, 1991).

In general, pronation and supination have been linked to a variety of lower leg problems. The distal (ankle) joint is the most unstable joint of the lower extremity because it does not exhibit coupled (simultaneously controlled by the brain) motion as do the hip
and knee joints (Beuter and Duda, 1985). The ankle joint is independently controlled by the brain. This is an advantage for ground contact adaptation but a disadvantage for stability.

Kernozeck and Greer (1993) postulated that most lower extremity injuries in women are at the knee and ankle as opposed to the hip or foot. Jernick and Heifitz (1979, as quoted in Clarke, Frederick, and Hamill, 1983, 11) studied chondromalacia patellae (degenerative disease of the knee cap) which may be aggravated by a lack of rearfoot stability. Van Woensel and Cavanagh (1992) linked an abnormal motion of the subtalar joint (a joint linking the heel bone to the rest of the foot) to knee injury. Hamill, Bates, and Holt (1992) associated iliotibial band syndrome with overpronation. They thought that an offset in the timing between subtalar and knee joints due to excessive pronation may lead to knee joint problems later.

Therefore, it is important to add to the body of knowledge on the function of feet as they relate to high-heeled footwear, so that scientific findings can be translated into changes in shoe design for shoe manufacturers. Gastwirth, O'Brien, Nelson, Manger, and Kindig (1991) have indicated the need for better high-heeled shoe designs which allow adequate rearfoot stability in order to improve function and comfort when walking. It is evident from the prevalence of using athletic shoes for everyday wear (Silverman, 1991b) and the popularity of such relaxed-looking shoes as Birkenstock® that comfort has become very important to the shoe-buying public. The majority of baby boomers are in the middle part of their careers and have found that their bodies are aging. They are in a position where they do not have to follow as much as they used to and want a little more comfort in their apparel and shoe choices.
Purpose of the Study

The purpose of this study was to compare rearfoot stability in the performance of women's high-heeled shoes with different heel dimensions. Gastwirth et al. (1991) have pointed out the need to study high-heeled shoes that have a small heel surface area (i.e., a narrow heel as opposed to a broad heel). There are many questions about high heels which could be investigated, but this study will focus on the parameters related to the stability of three heel styles. Several researchers commented on the influence of high heels on women's as well as men's gait, although men do not tend to wear high heels (platforms, cowboy boots) as high or as often as women do (Soames and Evans, 1987).

Often the justifications used to promote so-called healthy high-heeled shoes do not have a sound scientific basis. A variety of questions related to high-heeled shoes, such as the shape of the toebox, the incline and slope of the heel, the composition of the sole and rearfoot stability would be among the first questions which need to be answered. Stacoff, Kälin, and Stüssi (1991) suggested that large rearfoot movements imply that more support is needed. Kinoshita, Ikuta, and Okada (1990) have stated the need for dynamic (walking) rather than static (standing) examination of the rearfoot angle. The shoe industry and ultimately the consumers of high-heeled shoes will benefit from additional knowledge about the influence of high heels on human gait.

In this study the rearfoot angular stability (range of rearfoot motion) of women walking in two heel heights was investigated. Three shoe styles were compared: flat shoes, high narrow heels, and high broad heels (both narrow and high broad heels were 2 1/2 inches [6.4 cm] in height). The shoes were of very similar upper construction. The differences between the three shoe styles with regard to rearfoot angular stability were expected to be substantial.
Objectives of the Study

In order to achieve the purpose of this study, the following objectives were formulated:

1. To develop a procedure to compare the kinematic observations of rearfoot stability while walking on a treadmill in two high-heeled shoes with different heel types to that of walking in a flat shoe (this constitutes a total of three pairs of shoe styles) between subjects.

2. To compare the results of rearfoot angle measurements with the answers from the questionnaire for the three different types of shoe styles (two high heels and one flat).

Hypotheses

**Hypothesis 1:** There will be a difference between rearfoot stability in high heels and flat shoes.

a. There will be a difference between the maximum pronation angles in high heels and flat shoes.

b. There will be a difference between the minimum pronation angles in high heels and flat shoes.

c. There will be a difference between the pronation angles at heel strike in high heels and flat shoes.

d. There will be a difference between time to maximum pronation angles in high heels and flat shoes.

e. There will be a difference between time to minimum pronation angles in high heels and flat shoes.

f. There will be a difference between stance time in high heels and flat shoes.
g. There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the minimum pronation angle.

h. There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the pronation angle at heel strike.

**Hypothesis 2:** There will be a difference between rearfoot stability in high narrow heels and high broad heels.

a. There will be a difference between maximum pronation angles in high narrow heels and high broad heels.

b. There will be a difference between minimum pronation angles in high narrow heels and high broad heels.

c. There will be a difference between pronation angles at heel strike in high narrow heels and high broad heels.

d. There will be a difference between time to maximum pronation angles in high narrow heels and high broad heels.

e. There will be a difference between time to minimum pronation angles in high narrow heels and high broad heels.

f. There will be a difference between stance times in high narrow heels and high broad heels.

g. There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the minimum pronation angle.

h. There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the pronation angle at heel strike.
Limitations of the Study

The current study was limited to the female population, since problems with wearing high heels are of most concern to this group. In order to keep experimental costs low, the subjects had to fit a specified range of parameters with regard to age, height, weight, shoe size, and frequency of wearing high heels. This limits the ability to generalize results to that part of the female population which also fits these parameters. In addition, this study investigated rearfoot stability in isolation from other movements about the subtalar joint (a joint in the foot linking the heel bone to the rest of the foot). Pronation and supination angles in shoes were also evaluated in isolation (Van Woensel and Cavanagh, 1992). This investigation did not attempt to explain interrelationships with other parts of the body (Beuter and Duda, 1985) when making inferences about human gait.

Assumptions of the Study

Over the years there has been some debate about whether walking on a treadmill adequately resembles overground walking. Adequate in this case means whether one can make inferences from a study conducted with subjects walking on a treadmill compared to what actually happens when they walk overground. As has been shown by Taves, Charteris, and Wall (1983), treadmill walking represents a reasonable approximation of overground walking on a flat surface after allowing the subjects an adequate habituation period. Boda, Tapp, and Findley (1994), on the other hand, showed that there may be some differences which are especially pronounced in slow speed walking. However, Lafortune, Hennig, and Milani (1994) found no differences between overground and treadmill running in their comparison. Boda et al., who did not recommend using a treadmill did not look at rearfoot motion, the parameter under investigation in this study.
Since high heels are used mostly on flat surfaces such as indoor flooring, asphalt, or concrete walkways, use of a treadmill as a method of measurement is thought to represent an adequate means of assessing rearfoot stability.

It was assumed that subjects truthfully and honestly answered the questionnaire regarding their past shoe-wearing history. Since subjects were asked to answer a large number of questions, it was possible that some women were not able to answer every question with complete certainty. It was assumed that this was due to the inability to recollect exact facts with certainty rather than malicious intent. Since there was no mention made of a particular foot shape being linked to any specific anthropomorphic characteristics in the literature (for example, not all women who work for real estate agencies have a specific footshape), it was assumed that seeking subjects among a particular population did not select for a particular footshape and condition.

Since all subjects said they normally wear B-width shoes (the width of the test shoes), it was assumed that the movement of the foot within the shoe would be minimal and not of major concern to the outcome of the study (Stacoff, Reinschmidt, and Stüssi, 1992), especially since high heels usually fit more snugly than running shoes. Eversion and inversion (see definitions below) in walking take place with a fixed foot (during the ground contact phase) or a fixed shank (during the swing phase). Only the eversion and inversion taking place with a fixed foot during the ground contact phase leading to either pronation or supination was considered in this study.

Contextual Definitions

The following definitions may assist in understanding the following chapters. Many researchers use the same words but have a slightly different meaning in mind when using
them. To be absolutely clear in which way these terms are used in the present thesis, working definitions for terms used in this thesis follow:

**Flat shoe:** A shoe heel displaying a difference between the sole of the foot and the heel of the foot of no more than one-half inch [1.2 cm].

![Figure 1.1: Flat shoe](image)

**Mid heel:** A term used by the shoe industry to refer to a shoe approximately one inch [2.5 cm] to two inches [5 cm] in height. This style was not used in this study.
High broad heel: A shoe heel displaying a difference in height between the sole of the foot and the heel of the foot of more than two inches with a broad heel (more than \(1/6 \text{ in}^2 \) [\(1 \text{ cm}^2\)]).

Figure 1.2: High broad heel

High narrow heel: A shoe heel displaying a difference in height between the sole of the foot and the heel of the foot of more than two inches with a narrow heel (less than \(1/6 \text{ in}^2 \) [\(1 \text{ cm}^2\)]).

Figure 1.3: High narrow heel
<table>
<thead>
<tr>
<th><strong>Shoe Upper:</strong></th>
<th>Sides and top of the shoe, which may be constructed of a variety of different pattern pieces and materials (Tucker, 1985, p. 29).</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Heel counter:</strong></td>
<td>A firm cup at the back of the heel which centers the foot and keeps it stable as the foot strikes the ground (Tucker, 1985, p. 29).</td>
</tr>
<tr>
<td><strong>Comfort:</strong></td>
<td>A neutral sensation, when people are physically and psychologically unaware of the shoes they are wearing and the gait pattern and stability of the foot most approximate that of the healthy unshod foot (adapted from Smith, 1986).</td>
</tr>
<tr>
<td><strong>Gait:</strong></td>
<td>Erect biped locomotion involving the lower extremities which has some uniquely uniform characteristics in all persons. Joint angle patterns, moment of force patterns and mechanical patterns are consistent with regard to stride period. Muscle activity remains consistent but increases in amplitude as speed increases (adapted from Winter, 1983).</td>
</tr>
<tr>
<td><strong>Stride period:</strong></td>
<td>The period from heel strike of one limb to the next heel strike of the same limb is considered 100% of stride period (from Winter, 1983). 'Stance time' and 'swing time' are fractions thereof.</td>
</tr>
<tr>
<td><strong>Stance time:</strong></td>
<td>The time from first to last foot-to-ground contact. Usually this means from heel-strike to toe-off of one foot.</td>
</tr>
<tr>
<td><strong>Swing time:</strong></td>
<td>The period during which a limb is without contact to the ground -- the time from toe-off until heel-strike.</td>
</tr>
<tr>
<td>Term</td>
<td>Description</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Cadence</td>
<td>The beat, rate or measure of a rhythmic movement such as walking (measured in cycles or strides per second or per minute).</td>
</tr>
<tr>
<td>Foot strike pattern</td>
<td>This is determined by the area under the foot with which a person first touches the ground or walking surface. Usually this is with the heel (heel striker) but may be the midfoot (midfoot striker) or the toe (toe striker).</td>
</tr>
<tr>
<td>Digitizing</td>
<td>A method of capturing body landmark locations in space in a digital format. This can be done either manually or automatically using software algorithms to locate points which have been illuminated on film or video with the help of reflective markers.</td>
</tr>
<tr>
<td>Foot arch</td>
<td>The structure creating a void under the foot which helps in the spring action of the foot during walking.</td>
</tr>
<tr>
<td>Eversion</td>
<td>An outward turning movement about the inside edge of the foot, assuming an axis along the length of the foot.</td>
</tr>
<tr>
<td>Inversion</td>
<td>An inward turning movement about the outside edge of the foot, assuming an axis along the length of the foot.</td>
</tr>
</tbody>
</table>
Pronation: Eversion (outward turning) of the calcaneus (heel bone) relative to the midline of the lower leg. This measurement is used to approximate the true action of pronation (adapted from Bates, Osternig, Mason and James, 1978; Hamill, Bates and Holt, 1992). Brody (1986) stated that in normal walking "pronation unlocks the foot for surface adaptation" and Van Woensel and Cavanagh (1992) explained that "pronation has a damping effect on the impact loading of the foot."

Supination: Inversion (inward turning) of the calcaneus relative to the midline of the lower leg. This measurement is used to approximate the true action of supination (adapted from Bates, Osternig, Mason, and James, 1978).
Maximum pronation angle: The maximum angle in degrees measured during stance time.

Minimum pronation angle: The minimum angle in degrees measured during stance time or shortly before stance time. Since this angle was so different from the pronation angle at heel strike, it was felt to be important to report it.

Rearfoot range of motion: Total range of angular motion using the value for the maximum pronation angle minus the minimum pronation angle. Commonly the value for the pronation angle at heel strike is used for this calculation. In this study, the true minimum pronation angle was also used to calculate this value, resulting in two values for range of rearfoot motion.

Rearfoot stability: Amount and/or rate of foot pronation and/or supination of a person immediately following foot strike which is influenced by the shoe worn.

Summary

In contrast to athletic footwear, rearfoot stability in high-heeled shoes has not been studied much to date. Since high heels are a major component of women’s career apparel and will probably continue to be so, it is important to study them more closely. Studying the biomechanical aspects of high-heeled shoes will contribute to the information available to shoe designers and health professionals. The information provided by the questionnaire used in this study gives additional information about consumer shoe preferences. Terms used in this study have been defined for the benefit of the reader.
CHAPTER II
REVIEW OF RELATED LITERATURE

History and Evolution of the High-Heeled Shoe

The following section examines the historical development of shoes and especially the high-heeled shoe in ancient times, after the Renaissance, and in modern times. In addition, concerns raised during the Dress Reform Movement and high heels in a modern social context are discussed.

Footwear in Ancient Times

Shoes are the body coverings that protect the appendages that carry us through the world and are therefore invested with much meaning. Shoes have often been the subject of fairy tales and stories, such as ‘Cinderella’, ‘The Old Woman who Lived in a Shoe’ and others (Wright, 1922). It is not exactly known when prehistoric humans started using footwear, but it must have been a practical consideration. Humans wore and continue to wear shoes to avoid injury and discomfort when walking over uncomfortable ground. As far as known, the oldest shoes found on the North American continent are grass sandals or slippers found in Oregon which date back ten thousand years or more. Seventy-five sandals in good condition in volcanic ash were found in Fort Rock Caves (central Oregon: township 25 S, range 14 E, section 29; Cressman, 1962) in 1938 and two or three sandals in poorly preserved condition in Catlow Cave No. 1 (southeast Oregon: township 33S, range R 31 E, section 9; Cressman, 1962).

More complete records of shoes are less than 5000 years old, mostly documenting shoes from Egypt and other Mediterranean countries. The sandals, slippers and bootlike
leggings from these areas were quite varied and showed a high level of craftsmanship in decoration, giving political, social and psychological cues to the observer. High-heeled shoes have not yet been found in these areas. The only type of high-heeled shoe known to have existed in ancient times is the Greek kothornos, a high platform shoe employed by actors on stage to make themselves taller and more visible to their audience (Wilcox, 1948).

We do not know for certain why high heels were first worn, but it may have been the desire to be noticed more by others through the increase of one’s physical height. The high-platform kothornos remained part of formal stage paraphernalia of many countries bordering the Mediterranean Sea for many centuries. Not until the sixteenth century do we have evidence that high heels appeared as a fashion item among non-stage people of the Western world (Wilcox 1948). The first documented voided high heels were worn in Italy and then spread to other countries. The style consisted of very high platform shoes, called chopines, that appeared like stilts. They were worn by both sexes of the highest social class. The idea for these shoes may have come from the Near East (also sometimes called the Orient which includes countries to the East and Southeast of the Mediterranean; Webster’s, 1989), especially Turkey, where similar shoes were used for protecting one’s slippers or feet from sand and mud (Wilcox, 1948) or which might have been a fashion in the Turkish harem (Trasko, 1989).

These “Venetian” chopines reached great heights, up to two feet, and were very hard or impossible to walk in unaided. Servants or gentlemen held one or both hands of a lady wearing chopines. Upper-class Venetian women who followed the fashion mainly traveled by gondola from place to place and were not expected to walk very much. Some gentlemen complained of the height of women wearing chopines. Shakespeare (1603, Hamlet; [Act II, Scene II, lines 423-425], 1899, p. 65; [lines 445-447], 1935, p. 63) made Hamlet exclaim: “By’r lady, your ladyship is nearer to heaven than when I saw you last, by the altitude of a chopine.” Trasko (1989, p. 14) stated that others generally regarded chopines as beneficial
because they were “indicative of an aristocratic standard -- the less a woman walked, the higher her social prominence. The church favored the style as well, reasoning that if women could not move about freely, there would be much less sin.”

**High-Heeled Shoes Worn since the Renaissance**

Near the end of the sixteenth century, about 1590, a high heel similar to the one we are familiar with today became popular, first in Italy and then throughout the rest of Europe. It may have been Catherine de Medici, a woman of short stature, who brought high heels to Paris for her wedding to Henry II (Rossi, 1977). A similar heel had been known in other countries -- the Egyptian butcher used it to lift himself off the ground when slaughtering, and the Mongolian horseman’s shoe had a heel to avoid slipping out of the stirrup (Wilcox, 1948). The heel with a cut-away portion under the arch, however, was considered newly invented in Europe at the end of the sixteenth century. Some attributed the high heel to an inventive Italian shoemaker and his chopine customer; others attributed it to Leonardo da Vinci (Wilcox, 1948). If Leonardo (1452-1519) invented the high heel, it certainly took some time to become fashionable, for it was not until the 1590’s, about seventy years after Leonardo’s death that it became fashionable.

According to June Swann (1982), high heels and straights, that is shoes which can be worn on either foot, arrived for men and women at about the same time. Straight lasts have been “...occasionally used through history: for pointed toe Coptic shoes, 5-6th centuries; wide round toes circa 1490-1530, and especially for the platform-sole shoes of the 15-16th centuries” (June Swann, 1982 p. 59). It was very costly for craftsmen to stock left and right lasts for each heel height and shoe size, so using straights alleviated some of the financial strain for shoemakers in adapting to the new fashion for high-heeled shoes (J. Swann, personal communication, February 10, 1994). The straight pattern was abandoned
for use of left and right lasts again after heels disappeared shortly after the French
revolution (1789). In addition, the invention of the pantograph (an instrument for
duplicating technical plans on any scale) in the 1820s decreased the cost of carving pairs of
lasts. Many shoemakers adapted this process, to use left and right lasts, again some time
after the 1800s (J. Swann, personal communication, February 10, 1994). The impression
that straights were used much beyond the beginning of the nineteenth century may result
from the flood of mass-produced women’s shoes from France which were imported to the
United States and other countries from the 1820s on. Many of these imported shoes are
preserved in museums around the country, whereas finding handmade lefts and rights is
more rare (J. A. Butterworth, personal communication, February 20, 1994). Making lefts
and rights in the production of high-heeled shoes no longer poses a hurdle with today’s
modern technology, although “...some manufacturers are contemplating using straights
again in order to compete with Third World imports” (J. Swann, personal communication,
February 10, 1994).

The height of the heel in the early Stuart period (1603-1714) was quite moderate,
around two inches in height for both sexes, short in comparison to the extreme height of
chopines. During the Stuart period, horse riding was the principal mode of transportation,
at least for men, which necessitated a sturdy, moderately high-heeled boot with attachments
for spurs. Women’s shoes had similar heel heights but were cut lower in front and more
elaborately decorated since most women did not venture out as much and traveled in
protected coaches rather than on horseback.

For nearly two hundred years, from 1590 to about 1800, the height of the heel
remained approximately the same but the shape of the heel as well as the toe box changed
often, according to the prevailing fashion (Wilcox, 1948, Swann, 1982). With the
beginning of the reign of Napoleon (1804-1815), high heels nearly disappeared for men’s
footwear, retaining low heels only for riding boots and became quite low for women, too.
The baby Louis heel and the soft slipper, a ballet-type shoe, were the most popular shapes throughout the nineteenth century. Many inventions in materials and production, such as rubberized inserts and the beginnings of mass manufacturing, made changes in execution and decoration, rather than structure, quite exciting. These changes in shoe decoration corresponded with similar tendencies for garments. The United States did not begin significant manufacturing of shoes until the nineteenth century. Even then they mainly produced work boots and provided manufacturing equipment inventions (Wilcox, 1948) but continued to import their fashion shoes (including high heels) from Europe. It was not until the twentieth century that the United States was able to manufacture fashion shoes in a significant number to satisfy the fashion shoe needs of the population.

High-Heeled Shoes in Modern Times

At the height of the Industrial Revolution (around 1850) heels for men were passé. Aristocracy had declined, and social esteem could be achieved by being a successful business man rather than a leisurely aristocrat. At this time, men lavished sumptuous clothing and shoes upon their wives and women friends because this proved their purchasing power and thus their financial success (Veblen, 1912). It is possible that this is the reason for the resurgence of high heels during hard economic times—their obvious extravagance serves as a symbol of financial security to others.

The twentieth century was marked by a great boom in manufacturing and technological development that made it possible for fashions to start changing more rapidly, to be comparatively inexpensive, and to be widely available. This enabled people to own a multitude of footwear for different occasions. The advent of a variety of sports which could be performed by women, as well as the beginnings of the suffrage movement and the demand of equal rights for women, required flatter, more comfortable shoes. To be able to
perform strenuous physical activities, such as golf, tennis, bicycling or long-distance walking (for example, to conduct political campaigns), footwear had to be functional and comfortable. This led to a segmentation of the footwear market. Several different styles of shoes were used to perform different activities. One could own a pair of high heels just “for fun.” Fashion, therefore, provided a strong comeback for high heels at the outset of the century and reached a far larger segment of the population. Toward the end of the 1930s, near the beginning of the second World War heels reached the highest heights since chopines were in fashion (Wohl, 1941) showing how far manufacturing could take extravagance.

Trasko (1989) contended that, especially in this century, high heels have been associated with femininity and female sexuality. Extremely high heels were revived again during the 1950s after WW II. Many women who had joined the war effort by holding jobs previously considered “men’s work” wore functional work clothing including boots during the war. A lack of outlet for feminine expression in addition to wartime restrictions made women crave more elaborate dress. Men were eager to reclaim their positions in industry after WW II by sending women back to the home and women were eager to dress in feminine attire to welcome men home. Heels not only became very high but also very narrow. This was made possible by the invention of the stiletto heel with a stable steel insert. “Top shoemakers were featuring fantastically high, narrow heels by 1951, but the great vogue was in the later ‘fifties’ and it continued into the ‘sixties’” (Ewing, 1986, p. 86). These shoes hampered the ability of women to walk long distances or perform very physical tasks, although it had become common to have “tennis shoes” for sport activities and oxfords or loafers for walking.

The daughters of these women, the post-war baby boomers, grew up in the tumultuous 1960s. They rebelled against their mother’s dress code and initiated a movement for equal rights. The great number of baby boomers radically influenced
fashion. This was expressed in a very young look (King, 1963), accompanied by flat or very low-heeled shoes. According to Probert (1981), the late 1960s constituted a reversion to the 1920s, in terms of boyish, non-feminine fashions.

In the 1970s, platform and wedge soles were fashionable. For the first time in nearly two centuries both sexes wore these high heels. Since then, fashion dissemination has been more individualistic. People wear high heels, sport shoes or some other type of footwear according to their personal tastes and lifestyles. We have become much more demanding consumers, especially of clothing. It is almost certain that our need and desire for comfort as well as good looks will extend into the fashion footwear area. This is evident by the large gain in popularity of Birkenstock® sandals and other comfort shoes. Birkenstock® sandals and shoes are now available in many fashion colors and have gained some acceptance as appropriate wear to the office or other semi-formal occasions. They are worn in many countries in Europe, in the United States, and have lately become quite the hit in Japan as well (D. Watson, personal communication, July 21, 1995).

Shoe Concerns Raised during the Dress Reform Movement

Throughout history, shoes have been more or less comfortable, depending on the fashion of the time. When reading articles in current women’s magazines lamenting the lack of comfort of high heels, one wonders why it has been so difficult to change them. Since the Renaissance and the advent of wearing high-heeled shoes, there have always been voices that were in favor of improving the quality and comfort of women’s clothing and footwear. These reformers mainly worked through social channels. They have often been labeled ‘feminist’ and have therefore not been able to generate the political clout to quickly bring about change (Grossbard and Merkel, 1990). But slowly, over the course of several hundred years, the changes demanded are being implemented. There has been a tendency
for Western cultures to point out the “savage” practices of other, especially non-Western, cultures. For example, the binding of the foot to create a “lily-foot”, popular in China for centuries, has been widely criticized. However, the foot problems caused by Western shoes have not been equally scrutinized (Steele, 1985).

Early literary sources discussed and debated established clothing conventions and their merit. The characters of William Shakespeare, who lived from 1564 to 1616, often cross-dressed. Around 1620 a fierce debate arose regarding the propriety of women who wore men’s dress and conversely men who wore more feminine dress, respectively labeled with the Latin expressions: *Hic Mulier* (women in men’s dress) and *Haec Vir* (men in women’s dress). According to the few women practicing cross-dressing in the seventeenth century, “male garments ... confer not only the superior status of men but also freedom and ease” (Clark, 1985, p. 169). Men were afraid that “if a woman discards the restrictions proper to her sex in one way, ..., she will not scruple to do so in any other” (Clark, 1985, p. 169). These quotes show that the longing to cross social boundaries is not new to our times and is often symbolized by adopting the clothing (including the shoes) of the coveted social position. The resistance to the desire for more comfortable clothing by women had its roots in misogynistic and paternal attitudes of men. It signaled the feminist power struggle to come. This early discussion, though, was quickly squelched by King James in England who ordered his clergy to preach against the ‘masculine woman’ from the pulpit (Clark, 1985).

In another attempt to reform women’s dress, the bloomer costume (consisting of a fitted bodice and harem-like pants) included low-heeled or flat shoes and finally reached popularity during the bicycling rage at the end of the nineteenth century, more than fifty years after its inception (Grossbard and Merkel, 1990). It was actually first advocated during the dress reform movement of the nineteenth century by socialites of the time. It was named for one of the early advocates of dress reform: Amelia Bloomer (1818 - 1894) from
New York, who wore it along with some of her friends. The bloomer costume was introduced around 1850 in the U.S. (Webster's, 1989) and 1851 in the U.K. (Laver, 1985) and received more notoriety than followers. The outfit proposed by these women became widely known as a radical departure from acceptable dress.

The Dress Reform Movement was propagated by the social avant-garde during the 1870s, 80s, and 90s. They more or less followed some form of Delsartean philosophy (François Delsarte, French musician and teacher of body movements and physical culture including reformed dress, Meckel, 1989). Many physicians supported the dress reform movement as well. They were especially concerned with the ill effects the dress mode of the time (especially the corset but also shoes) had on women’s health (Cunningham, 1990).

The dress reform topic was so popular that speakers filled lecture halls. One influential lecture series was arranged by Abba Goold Woolson in 1874 and later published in book form. The series included speeches by four woman physicians on their experiences in their medical practice as well as some solutions offered by the author. Most of the physicians not only spoke on the ill effects of the corset but also devoted some time to the topic of shoes, and high heels in particular (Goold Woolson, 1874). Mercy B. Jackson lamented:

The Chinese shock our moral sense when they deform the feet of their women by merciless compression in infancy; but we at the same time tolerate - nay, encourage - ours in wearing such covering as lays the foundation for consequences more fatal than theirs. The high heels which have been so fashionable, but which now, happily, less used, are one of the most fruitful sources of disease. They not only cause contractions of the muscles of the leg, so great in some instances as to make a surgical separation of them necessary, but by raising the heel they bring the weight of the body upon the toes, and thus induce the corns and bunions that alone suffice to make locomotion very painful. (Goold Woolson, 1874, pp. 75-76)

Goold Woolson (1874, p. 162, pp. 191-192) was in favor of using “the best of Miller’s broad-soled boots” and taking “special pains ... to protect the feet with warm coverings, to elevate their soles above the ground, by many layers of stout leather rendered nearly impervious to cold and moisture, and alas, to give as much freedom to the movements of the feet beneath their coverings as ease in walking will allow."
At the height of the public discussion of the aesthetic (dress reform) movement during the late 1880s and early 1890s some medical journals, such as the British Lancet, regularly published articles specifically attacking the problems with high heeled shoes (Steele, 1985). Towards the last decade of the nineteenth century the dress reform movement lost some of its power especially due to the gradual obsolescence of the corset and the popularity of lower-heeled shoes through a change in fashion. Its impact in bringing about this change and changes in the use of footwear is not well documented but a variety of factors played a role.

The twentieth century has not seen a dress reform movement as such. But, the women’s movement of the 1960s and 1970s and continuing to the present day, has played a role in the development of current fashions. The debate over high heeled shoes has by no means subsided. In the 1980s,

... women (who used to be criticized by men for wearing foolish and unhealthy high-heeled shoes) turned to wearing running shoes with their business suits while walking to the office. But an op-ed [opinion editorial] column in the New York Times declared that this was “A Sneaking Problem for Men.” It does not look professional, complained Richard M. Goldstein, adding that women used to be able to wear high heels. An angry woman wrote in reply to complain about “High-Heeled Instruments of Torture.” (Kidwell and Steele, 1989, p. 88)

The popularity of high heels at the end of the twentieth century still waxes and wanes with fashion trends.

High-Heeled Shoes in Contemporary Social Context

In society today, the high-heeled shoe is seen as more than a fashionable item. High-heeled shoes have been more or less tied to the social status of women during their struggle for a more powerful position in Western society. They have become a symbol of femininity and submission as opposed to masculinity and power. According to William Rossi,
Most shoes in the United States and throughout the world are designed by men. Definitely this isn't because men have more designing talent than women. Partly it's due to tradition. But a large share is due to the simple truth that men, heterosexual men, have a psychosexual desire to dress and undress women head to toe. If women dress chiefly to be attractive to men, then the male designer feels it is both his right and his duty to select the clothes and footwear they wear to please him. And most women seem to prefer it this way. (Rossi, 1977, p.82)

The sentiment that "foot position affects leg shape in a visually pleasing manner" has been confirmed by several men during discussions about this research project (M. De Beliso and others, personal communication, 1992). If a woman stands on the balls of her feet, or in high heels, the leg takes on contours and muscle undulations that don't exist when the foot is flat on the ground" (Rossi, 1977, p. 231). The shortening of the gastrocnemius and soleus muscles makes the calf look more shapely and the ankle more slim. In addition to the factors mentioned by Rossi, the decreased stride length and increased step frequency are also found attractive by some men. Rossi (1977) believes that high-heeled shoes will remain popular in the future. If they do, there is a need for studying the effects of formal, high fashion, and career footwear on women's feet and bodies.

The United States has a large proportion of working women. In 1988, 68.5% of all women under age 60 in the United States worked. This is similar to the proportion (55-80%) of working women in other Western countries (Monthly Labor Review, 1990). Some of the working women are in management and leadership positions requiring appropriate career apparel and shoes. In the 1970s when women moved into the workforce in large numbers, career apparel consisted of modified men's wear, usually a suit including a tailored jacket and skirt and a modest blouse. Shoes, however, were decidedly feminine, with high heels being the norm. As women became more established in the corporate world in the 1980s, they conformed to the dress code of high-heeled shoes at work but wore tennis shoes during their commute, carrying their dress shoes in a bag. This habit was not only to conserve wear on expensive shoes but for comfort as well (V. Bedford, personal communication, February 6, 1996; J. Kennelly, personal communication, February 2,
1996; V. Moreland, personal communication, February 3, 1996). It was not uncommon for women to work sixty or more hours a week in order to advance professionally and gain promotions. Aching feet were one of the facts of life which had to be endured.

To learn about the comfort aspects with regard to high-heeled shoes, one needs to investigate the research already performed by others on the same subject. Although running shoes have been extensively studied in the last twenty years, this is not so for high heels and other women's dress shoes. Research is scant, but one can still glean valuable information from what has been published about other types of shoes.

Studies of High-Heeled Shoes and Studies of Rearfoot Parameters

According to McAllister (1991), 88% of women (surveyed in a study by the University of Southern California School of Medicine and the American Orthopedic Foot and Ankle Society, n = 356, ages 20-60) wear shoes that are not comfortable with regard to length and width. In the same study, published two years later by Frey, Thompson, Smith, Sanders and Horstman (1993) it was indicated that most women suffer from some foot pain and have experienced the need to wear a larger shoe size since the age of 20. Many women prefer to wear fashionable shoes, such as high heels. However, this is changing according to the 1991 FIA (Footwear Industries of America) footwear manual. In the manual it was stated that in 1990, for the first time, athletic shoes were the most frequently purchased type of women's shoes. Athletic shoes represented 31% of all shoes sold. This was attributed to a shift in women's shoe needs. In the report, 46% of women stated comfort as the main factor influencing the purchase of a new pair of shoes (Silverman, 1991b).

Few shoe manufacturers have responded to women's need for more comfortable shoes. Dr. Louis C. Talarico Jr. from the Biomechanical Engineering and Shoe Research
Laboratory, Inc. in Lewiston, Maine contended that less than 1% of the population wears shoes that fit them anatomically (Tedeshi, 1991). The reason is that about 95% of the population display either a varus foot type (with a tendency to pronate) or a valgus foot type with a tendency to supinate (4% of the population) (Tedeshi, 1991). The remaining 1% reported no foot problems. These reports indicate a strong need to investigate rearfoot stability in women’s shoes in general and dress shoes such as high heels in particular.

Some women currently wear more comfortable high-heeled footwear (broad heels as opposed to narrow heels). This trend has been apparent since the early 1990s. At the same time, the fashion for grunge wear, started in the northwestern United States, made clunky shoes much more acceptable to wear. This influence has been felt in high heels as well. These trends indicate a desire by consumers for more comfortable shoes. Studies of women’s dress shoes could help in determining the best heel shapes for high heels in the future.

Athletic shoe companies have spent millions of dollars since the early 1980s to study the biomechanical aspects of gait to improve their shoes. This commitment to improving customers’ foot health has paid off. Sales and price structure of the athletic footwear market is very solid, according to Footwear News (Silverman, 1991a). Several studies investigating high-heeled shoes from a biomechanical perspective exist, but only four deal with rearfoot stability (Adrian and Karpovich, 1966; Ebbleing et al., 1994, Hontalas and Williams, 1995; Snow and Williams, 1994). The last three were not published when the data collection for this study was started and will therefore be discussed in Chapter 5.

To study shoes, the complexity of the anatomical makeup of the human foot has to be considered. Each foot is made up of 26 bones, small muscles, tendons, connective tissue and such specialized structures as the heel fat pad. The individualized arrangement of these components in each person makes it difficult to generalize too much about what is common to all humans and at the same time allow manufacturers to determine what makes the
'perfect' shoes for the 'general public'. This is especially difficult for high-heeled footwear. Studies which quantify the influence of high-heeled shoes on the foot and body from a biomechanical or medical perspective are described in the following pages. To gain more insight into what can be expected with regard to rearfoot stability, a number of studies about running and tennis shoes are discussed as well.

Postural Alignment

Postural alignment is the position of the limbs with regard to each other and within the body as a whole. High-heeled shoes are commonly thought to have a negative effect on the alignment of the human body. Therefore, many of the biomechanical studies conducted on the subject of women's high-heeled shoes before 1990 focused on postural alignment. A number of studies deal with the shifting of the pelvis when wearing high heels compared to flat shoes, although the results of different inquiries have been contradictory. Mathews and Wooten (1963), Bendix, Sørensen and Klausen (1984) and Opila (1988) found a significant backward shift in the center of gravity of women in high heels. Bendix et al. (1984) found that the ankle joint shifted towards the line of gravity, and the pelvis inclination decreased in high heels. Short (1986) showed a significant forward shift in the center of gravity in women wearing "high heels" (in her study an equivalently raised board was used to simulate high heels which may be different from real shoes). Her findings correspond with the postulation by Roaf (1977) that a forward shift in the center of mass occurs when wearing high heels. Roaf cautioned that footprint marks (taken with the Harris mat of pedobarography) may be of significance in evaluating posture only when walking because during stance, posture might be unconsciously adjusted.

Although many attempts have been made to quantify good posture, (MacEwan and Howe, 1932; Massey, 1943) the results of these studies do not confirm a consensus of
opinion. Roaf (1977) asserted that high heels require continued muscular activity for flexing knees and arching the lumbar spine backwards, a clinical observation that is substantiated by the increased spinal curvature (lumbar lordosis) in habitual high heel wearers. However, others have found a flattening of the lumbar spine in high heel wearers in empirical studies (Bendix, et al. 1984; DeLateur, Giaconi, Questad, Ko and Lehmann 1991; Opila, 1988). Opila-Correia (1990b) found differences in the degree of lumbar lordosis for subjects of different ages. For younger subjects, lumbar lordosis seemed to increase whereas for older subjects it decreased when wearing high heels. Her study indicated a correlation between high-heeled gait parameters and years of wearing high heels by subjects. This indicates that habitual wearing of high heels may cause posture compensation.

Inman, Ralston and Todd (1981) stated that when weight is shifted onto the toes, the body weight is transferred to the forefoot, heels invert, legs rotate externally, and the longitudinal foot arches rise. A rise in arch height after wearing high heels the entire day has also been shown by Ricci and Karpovich (1964). These observations are further substantiated by Opila, Wagner, Schiowitz and Chen (1988) who, on the other hand, admit to a sizable variation among individuals in their sample. A rise in arch height has not been associated with any detrimental effects on the foot but is interesting to researchers to understand better the influence of heels on foot function. In her work on postural alignment as it relates to weight gain, Opila (1988, 145) stated "... that females have greater adaptability to anterior loads such as that imposed by pregnancy or high-heeled shoes [although this increases] the loads on the discs." Since feet constitute the support structure for the body, shoes have a major effect on body posture, especially in high-heeled shoes.
Gait Analysis

In the past, many studies of high heels have measured static posture because it was hard to quantify measurements during walking. Since most women who wear high heels do a moderate amount of walking in them, these stationary studies are only somewhat helpful. In the past few years, techniques for measuring human movement parameters have vastly improved due to advances in sports research.

Some of the early investigations of high heels were almost exclusively performed by Peter Karpovich and his colleagues. Karpovich studied the joint angles present in the knee and ankle during standing, walking and running in high heels. In a supplement of Research Quarterly (Adrian and Karpovich, 1964; Gollnick, Tipton and Karpovich, 1964; Finley and Karpovich, 1964) three researchers who worked with Karpovich presented the findings of their collaborations. Adrian and Karpovich (1964) did not find much difference between the knee angles measured in cowboy boots (2 1/4" heels) and bare feet during standing, walking and running, whereas Gollnick, Tipton and Karpovich (1964) found that there was a ten-to-fifteen degree increase in extension and a ten degree decrease in flexion in the knee during running in high heels. These two studies, as well as Finley and Karpovich (1964), employed electrogoniometers, devices which measure joint angles, such as the knee or ankle. Adrian and Karpovich (1966) found decreased step length, total range of movement and out-toeing (toes point outward during walking) in high heels.

Gehlsen, Braatz and Assmann (1986) observed decreased stride time and knee joint flexion. Gollnick, Tipton and Karpovich (1964) also showed a tendency for increased knee extension. Likewise, slower velocities resulting from shorter stride lengths (Gehlsen, Braatz and Assmann, 1986; Merrifield, 1971; Murray, Kory and Sepic, 1970) and decreased step length but a minimum change in stride width and foot angle (Merrifield, 1971) were observed in high heels.
More recently, Opila-Correia (1990a, 1990b) investigated gait parameters in high-heeled and low-heeled shoes, looking at angles of rotation at the knee, hip, pelvis, upper trunk and trunk during treadmill walking. She found significant differences in the knee and hip parameters between the two conditions and also significant differences between experienced and inexperienced high heel wearers and younger and older subjects. Studying the way feet perform in high heels during gait is very important because this is how shoes are generally used. Comparing gait in high-heeled shoes with that of low-heeled or flat shoes shows whether or not there is a difference between them. Gait analysis has become the method recognized as the most feasible way of evaluating rearfoot stability.

**Oxygen Expenditure and Joint Angle Measurements**

Although alignment, foot pressure and gait analysis may seem to be the most obvious aspects to study with regard to high heels, researchers have also looked at a variety of other relationships. Oxygen consumption during walking in different heel heights is an aspect which has been studied, and it was found that “high heels were significantly more costly in energy than either bare feet, saddles or loafers” (Mathews and Wooten, 1963, 570). Joseph and Nightingale (1956) detected some increased activity in the soleus (calf) muscle during standing which might be attributed to its taking up the slack of the Achilles tendon for subjects not used to wearing high-heeled footwear or to the instability in posture while wearing high heels. Lee, Shieh, Matteliano and Smiehorowski (1990) found a decrease in gastrocnemius muscle (calf) and tibialis anterior muscle (front of lower leg) activity in women wearing high heels. This is in agreement with Joseph and Nightingale (1956) who also found a decrease in or no activity of the tibialis anterior, the vastus lateralis, the vastus medialis and hamstrings (the last three muscles are located in the thigh). This means that most of the work in maintaining stability when wearing high heels is performed by the calf muscles rather than the thigh muscles or the muscles of the front lower leg.
According to Neale (1981), there are only three consequences which might prove harmful in the continual wearing of high heels. The first results from wearing a shoe designed with a very narrow toe, which reduces the medio-lateral stability of the subtalar and ankle joints and leads to more work being performed by the tibial (calf muscle deep to the soleus) and peroneal (on the outside/lateral side of the lower leg) muscles in maintaining the balance of the body. This means that the shape of the toe area of the shoe has an influence on rearfoot stability. The second consequence is that the foot slips forward in a shoe with increased heel height. This might cram the toes into the toe box, deforming the first and second metatarsal and phalangeal bones into a bunion and causing skin irritations such as corns and calluses. These may lead to foot problems later in life. Neale recommended an insole which keeps the heel as nearly horizontal as possible and a strap or tie across the front of the ankle, a design popular in the 1930s and 1940s. These T-straps and Mary Janes are making a comeback and have always remained popular for ballroom dance and tap shoes which require more foot stability. The third consequence is that toes in high heels stay in a constantly dorsiflexed position on the metatarsal heads, and the triceps surae muscle group (gastrocnemius and soleus which shape the posterior calf) shortens permanently which might cause problems if a person who generally wears high heels switches to low heels. Either an acquired (through the constant wearing of high-heeled shoes) or a congenital shortness of the Achilles tendon (equinus) may cause problems when wearing low heels, and it may not be possible for such a person to wear very low heels at all. As can be seen from this group of studies, high-heeled footwear has been examined from a variety of perspectives. Although they may seem unrelated to the present study, these studies contribute to a general scientific base for the study of footwear.
Rearfoot Studies

Many studies involving the examination of pronation and supination have been performed in the field of biomechanics, although only one has involved high-heeled shoes (Ebbeling et al., 1994). Much can be learned about rearfoot stability from running shoe and tennis shoe studies. In the 1980s a trend started towards increasing the heel contact area of running shoes beyond regular straight heels. This was accomplished by adding extra material to the outsides of shoes, extending beyond the sides of the foot. Different amounts of material added created different slopes or angles generally referred to as heel flare. Increasing the heel flare increases the ground-contact area, leading to greater heel stability. Some researchers (Clarke et al., 1983, Stacoff et al., 1988, Van Woensel and Cavanagh, 1992) have investigated different heel flare (from 0 to 30 degrees [0, 15, 30; 10, 10, mixed; 10 varus, 10 valgus]) and their influence on rearfoot stability.

The ground-contact area is also of concern in high heels. Similar to the findings in running shoes, one would expect rearfoot stability to increase with increased ground-contact area in high heels. Of course, the speed of wearer’s movement encountered in running shoes and high heels is quite different, which may make the ground-contact area needed for stability different as well. Schnabel, Hennig and Milani (1994) found that rearfoot pronation increased with increasing speed in running. A tendency toward an optimal heel flare of approximately 10 degrees became apparent in running shoe studies in the 1990s (Van Woensel and Cavanagh, 1992). No heel flare and too much heel flare were both deemed disadvantages to rearfoot stability. Similarly, it may be possible to determine an optimal heel size for high heels.

One of the major concerns in rearfoot studies involving running shoes was the material from which the sole was made. Very soft soles tended to absorb more shock but provide no rearfoot stability. Hard soles, on the other hand, provided a great deal of stability but
had poor shock-absorbing properties. The aim of some biomechanical studies is to find an optimal balance in sole material properties. This has never been studied in high-heeled shoes but may present an interesting topic for further study.

Rearfoot Parameters

It is clear to most young girls and boys who try on their mom’s high-heeled footwear that donning the shoes and actually walking in them are two entirely different matters. One of the modern rites of passage may be when a young woman accomplishes the technique to walk gracefully wearing high heels. One of the first things one notices about an inexperienced high heel wearer is how unstable her walk appears. The whole body seems to lack stability, wobbling along. As with many skills, the ability to walk in high heels deteriorates with disuse. Foot instability was noted in women who wear high heels only occasionally (Lee, Matteliano, Medige and Smiehorowski, 1987). Runners are well aware of the need to try to adjust for pronation or supination when buying new shoes. Women who wear high heels should select shoes carefully, because they usually spend a good deal more time in their shoes than most recreational runners in theirs.

Adrian and Karpovich (1966) found a decrease in pronation in high heels compared to low heels but used an open-toed, sling back high-heeled shoe which may not yield applicable results due to a lack of stability inherent in the construction of the shoe. Gastwirth, O’Brien, Nelson, Manger and Kindig (1991) indicated a slight tendency towards increased supination in subjects wearing high heels. Soames and Evans (1987) indicated increasing lateral stability with increasing heel height and decreasing ground contact area. Tucker (1985) stated that persons with low arches and wider hips (which is true for many women) tend to pronate as much as 10 degrees from normal. Information about rearfoot stability in high heels could be very helpful in determining the 'ideal' range
of shapes for high-heeled shoes. Most of the information about rearfoot stability in high heels for this study was gleaned and inferred from articles which focused on the study of other topics such as running shoes because additional studies had not been published at that time.

Investigative Methods Used in Other Studies

The following section examines investigative methods used in other studies, especially kinematic data collection methods, possible sources for measurement error, and the issue of possible movement within the shoe.

Kinematic Data Collection Methods

The following section deals with different aspects involved in collecting subjects' kinematic data. These studies provide information to help determine the best method to collect data for this study. They include the description of reflective markers, advantages of the use of a treadmill over overground walking and three- versus two-dimensional measurement techniques, the importance of good resolution, the importance of providing visual cues for subjects during treadmill walking, an explanation for the foot chosen for filming, and a consideration of cadence and gait parameters.

Reference and Reflective Markers.

In order to measure rearfoot angles, one has to find some way to mark certain body landmarks in a reliable way and then to calculate the angles between the body landmarks. Over the past fifteen years, it has become common to use the digitized data from videotaped subjects which show reference markers on certain body landmarks for biomechanical
analysis. A number of researchers have used reference markers in their studies (Clarke, Frederick and Hamill, 1983, 1984; Engsberg and Andrews, 1987; Kernozek and Greer, 1993; Kernozek and Ricard, 1990; Kinoshita, Ikuta and Okada, 1990; Luethi, Frederick, Hawes and Nigg, 1986; Simpson, Shewokis, Alduwasain and Reeves, 1992; Soutas-Little, Beavis, Verstraete and Markus, 1987; Stacoff, Denoth, Kälin and Stüssi, 1988; Stacoff, Kälin and Stüssi, 1991; Stacoff, Reinschmidt and Stüssi, 1992 and Van Woensel and Cavanagh, 1992). Beuter and Duda (1985), Hamill, Bates and Holt (1992) and Murray, Kory and Sepic (1970) have used reflective markers illuminated by a spotlight for their data collection. Reflective markers have the advantage that they can be digitized automatically (conversion to computer coordinates; see definitions in Chapter 1). According to Engsberg and Andrews (1987) errors from digitizing the markers can be reduced by auto-digitizing. An additional advantage of reflective markers is that they allow for the use of the Qualisys® System, a camera system which picks up infrared light and is therefore very sensitive to the light reflected by the markers but not to other light sources in the room.

Treadmill versus Overground Walking.

Since it is more significant to study high-heeled shoes with the subjects walking rather than standing (that is, a dynamic study rather than a static one) it is best to use a treadmill. A treadmill is easier to use than an overground walkway because it is stationary while the subject is walking, thus minimizing perspective error. Although treadmill walking has been deemed different from floor surface walking by some (Lee, Matteliano, Medige and Smiehorowski, 1987; Boda, Tapp and Findley, 1994), results from another study indicate that after an adequate habituation period the differences between treadmill and overground walking are significantly reduced (Taves, Charteris and Wall, 1983).
Boda et. al. (1994) found the differences between treadmill and overground walking to be especially pronounced if subjects were walking at a very low speed (one mile/hour or 0.44 meters/second). This research group did not investigate rearfoot stability in their study. Another team, Lafortune et al.(1994), found no difference between pronation values when comparing running overground and running on two different treadmills. The differences between treadmill and overground walking are small enough to take advantage of the benefits the treadmill offers in collecting data more comfortably. It also reduces the variability between studies. This means data from different studies which used a treadmill can be compared more reliably.

Two-dimensional versus Three-dimensional Measurement Techniques.

Areblad, Nigg, Ekstrand, Olson and Ekstrøm (1990), Engsberg and Andrews (1987) and Soutas-Little, Beavis, Verstraete and Markus (1987) have studied whether it is necessary to use three-dimensional (two or more cameras) data collection methods instead of two-dimensional (one camera) methods to ensure exclusion of perspective errors when investigating rearfoot angular motion. Areblad et al. (1990) and Engsberg et al. (1987) thought the difference to be large enough to warrant the recommendation of the three-dimensional approach, whereas Soutas-Little et al. (1987) found relatively little difference. Stacoff et al. (1991) also contended that errors are relatively small and can be disregarded when looking at pronation and supination in rearfoot motion. Stacoff et al. (1992) used a two-dimensional procedure to find out whether there was any difference between the movement of the heel and the movement of the shoe counter in running shoes. Van Woensel and Cavanagh (1992) and Hamill, Bates and Holt (1992) thought the two-dimensional method to be satisfactory as well. While not all researchers believed that a three-dimensional approach was necessary, there are no disadvantages to its use and may, in fact, improve accuracy.
Resolution.

Clarke, Frederick and Hamill (1984) and Kernozek and Greer (1993) have shown the need to achieve good resolution of the image to aid in digitizing the video images and obtaining meaningful data. Resolution in filming refers to the ability to distinguish between two separate but adjacent objects or sources of light or between two nearly equal wavelengths. This means that either the human eye in manual digitizing or the automatic digitizing mechanism must be able to distinguish between pixels (picture elements, the smallest elements of an image that can be individually displayed) in the image.

Foot Angles / Dominant Hand and Foot.

According to Holden, Cavanagh, Williams and Bednarski (1983), for most subjects, the right foot angle is significantly larger than the left foot angle in walking and running, and the left foot abducts significantly less. Therefore, the left foot was often the foot measured in these studies. More recent studies have not given much weight to the study of one foot over the other. Matsusaka, Fujita, Hamamura, Norimatsu and Suzuki (1983) stated that the side of the dominant leg is usually opposite to the dominant arm. Of the 64 subjects in their study, 90% were right foot dominant. It follows then that most were left-handed.

It is important to consider the abduction/adduction or foot placement angle, that is, the degree the foot turns away from the midline (either positive = toe out or negative = pigeon toe). There is significantly less abduction with increasing speed. A study by Van Woensel and Cavanagh, for example, found that “... changes in rearfoot angle and velocity [are] consequent to variation in foot placement relative to the midline” (1992, p. 32). In other words, they found that the degree of out-toeing displayed by a subject directly influenced
the rearfoot angles observed. Kernozek and Ricard (1990) also indicated that persons showing a greater foot placement angle relative to the midline usually showed a greater pronation angle as well. The question is whether this has to do with perspective error or with a tendency for persons with a greater foot angle to show increased pronation. When three-dimensional kinematic measurements are used, perspective error is not an issue. Usually the rearfoot angle of the left foot is smaller, so it has been recommended to study that foot.

Cadence and Gait Parameters.

A question that arises when assessing human movement is whether stride length, cadence (rhythm or beat; see definitions in Chapter 1) or speed have any influence on the parameters to be investigated. Gastwirth et al. (1991) found that cadence within one subject was not different between barefoot, low heel and high heel tests. However, an increase of cadence for subjects wearing high heels was found by others (Gehlsen, Braatz and Assmann, 1986; Soames and Richardson, 1983; Yamasaki, Sasaki and Torii, 1991). Yamasaki, Sasaki and Torii (1991) stated that women may increase speed by increasing cadence but speed is mostly a function of body height in individuals. According to Soames and Richardson (1983) speed in high heels is altered by changing cadence rather than stride length and should be confined to certain limits in the design of a study. In some studies speed and cadence were not controlled (Soames and Evans, 1987) although angular measures are significantly different due to speed especially during double support (short period when both feet touch the ground) and early and late swing phases of the leg (Taves, Charteris and Wall, 1983). These concerns indicate the need to control speed, but not necessarily cadence and stride length (step length), when investigating rearfoot stability.
Measurement Error

A number of factors can contribute to measurement error. Perspective error due to camera placement or treadmill setup and placement of the reflective markers are two of these factors.

Perspective Error.

Perspective error is easily introduced to film data. Careless camera and treadmill setup can contribute to perspective error and thus to measurement error. A number of researchers discussed the need to limit perspective error when filming (Areblad et al. 1990; Bates et al. 1978; Bates et al. 1979; Engsberg et al. 1987; Kernozek and Greer, 1993; Kernozek and Ricard, 1990; Soutas-Little et al., 1987; Stacoff et al., 1988; Stacoff et al., 1991; Stacoff et al., 1992; Van Woensel and Cavanagh, 1992). Perspective error was not an issue in this study because of the restricted focus on the lower legs and feet and the use of three-dimensional data collection.

Marker Placement.

Poor placement of markers is prone to introduce a large degree of error into the data set. If markers are placed either without care or without skill, the results from angle calculations may be mildly to grossly skewed. Clarke et al. (1983, 1984) devised a method for good placement of reference markers on the leg. This method involves placing an adjustable measuring device around the knee joint from behind. It allows the determination of the geometric joint center in the frontal plane. A string drawn from the knee at midpoint to the center of the Achilles tendon makes it possible to place the marker below the belly of the gastrocnemius (the arc made by the calf muscle). The other marker is placed over the
Achilles tendon. This minimizes measurement errors due to misrepresentation of the axis of the lower leg. Clarke et al. (1983, 1984), Luethi et al. (1986), and Yingling, Yack and White (1994) used similar methods. Stacoff et al. (1992) suggested that skin movement may contribute to measurement errors. But, since the lower leg is not prone to accumulate much adipose tissue (fat) the skin movement is minimal in subjects not grossly overweight.

Movement of the Heel within the Shoe

The following section considers how foot movement within the test shoes could affect the present study.

Measurement Techniques.

When investigating gait parameters in shod feet, there is always an element of doubt regarding whether some measurement error may be introduced by the discrepancy between the movement of the foot and the movement of the shoe. The common testing method used for rearfoot stability is to place reflective markers on the center back (heel counter) of the shoe. Clarke, Frederick and Hamill (1984) cited papers by Clarke (1980) and Nigg (1981) in which windows were cut in the heel counter of shoes and the reference markers were affixed directly to the feet. The researchers aimed to determine if in-shoe foot motion was different from that observed on the heel counter of the shoe. Neither of these papers were published. The first published paper on the difference between shoe and foot movement in running shoes was by Stacoff et al. (1992) who found movement differences of the foot within the shoe of up to three degrees. They stressed the need for experimental shoes in rearfoot studies to be examined for good fit to ensure a reasonable representation of rearfoot stability by data gathered from the heel counter. The heel movement inside the shoe was less the better the shoe fit the subject.
Fit of Shoe and Uniformity of Construction.

Other researchers have also commented on the importance of a good shoe fit when investigating gait parameters. Clarke, Frederick and Hamill (1984) and Mathews and Wooten (1963) both made mention of it. Gastwirth et al. (1991) and Kinoshita et al. (1990) stressed the need to use shoes of uniform construction for all subjects. This could either be achieved by using the same shoe style or design or at least looking for a similar upper construction in all shoes. Some studies have not controlled for this parameter but let subjects wear their own shoes (Gehlsen et al., 1986; Merrifield, 1971; Opila-Correia, 1990a; and Soames and Evans, 1987). Soames and Evans (1987, 894) even let subjects decide "...what they considered to be medium and high-heeled shoes," a questionable practice in an empirical study. Merrifield (1971) had test shoes examined for good fit, and Lee et al. (1987) used shoes adjusted by a professional shoemaker to achieve homogeneity with regard to heel height for each subject (the shoe maker added the appropriate amount of additional rubber material).

Age and Experience of Subjects

The first consideration about subjects for this type of study was their age. Most young women do not start wearing high-heeled shoes until they are over fifteen years old. And, gait deteriorates as people reach 60 or older. In very young women, instability may be attributable to inexperience whereas in old women effects may be rooted in their deteriorating overall gait pattern and their decreasing choice of high heels for personal footwear. Murray, Kory and Sepic (1970) found strong age-related gait differences in subjects 60 and older and some differences in subjects 50 and older. This is in agreement with variance among subjects of different age levels or experience levels observed by
Opila-Correia (1990b). Lee, Shieh, Matteliano and Smiehorowski (1990) also stressed the need to use subjects experienced in wearing high heels. Therefore, age range of subjects is an important consideration.

Clinical Assessment

It is common procedure to perform a clinical assessment on subjects before admitting them to take part in a biomechanical study. This is done in order to determine whether unusual findings (outliers in the statistical analysis) can be attributed to peculiarities of the subject’s feet or indeed present a significant finding related to the shoes under investigation. Many researchers have done pre-trial examinations before allowing subjects to participate in their studies (Gastwirth et al., 1991; Hamill et al., 1992; Joseph and Nightingale, 1956; Kernozek and Ricard, 1990; Kernozek and Greer, 1993; Kinoshita et al., 1990; Merrifield, 1971; Simpson et al., 1992; Soames and Evans, 1987; and Snow et al. 1992). Kernozek and Ricard (1990) found that persons with low arches are most likely to exhibit pronation, persons with high arches are somewhat likely to exhibit pronation and subjects with normal arches are least likely to exhibit pronation. Excessive pronation can influence the outcome of rearfoot stability studies.

Foot Strike Pattern

Most healthy people strike the ground with their heel first when walking and then roll through the midfoot section before lifting off the toe (heel strikers). However, some individuals place the midfoot or forefoot first. The question arose whether to limit subjects to include heel strikers only in the present investigation. Several researchers have examined subjects with regard to their foot strike patterns before considering them for a study. Tucker (1985) contended that about 80% of the population is categorized as heel strikers.
with the remainder being midfoot or toe strikers. Some researchers therefore exclusively use subjects with a selected foot strike pattern to investigate a specific population. In addition, there is a possibility that wearing high heels may alter the foot strike pattern of subjects.

Several researchers have used only heel strikers in their studies (Clarke et al., 1983; Hamill et al., 1992; Kinoshita et al., 1990; Lee et al., 1987). Stacoff et al. (1991) investigated forefoot (midfoot or toe) strikers in particular because they were interested in sprinters who often use a toe strike pattern to achieve speed. Impact is decreased by changing from a heel to a toe strike pattern (Kinoshita et al., 1990). Freedman and Kent (1987) contended that the toe strike pattern is more efficient and stable and Lee, Matteliano, Medige and Smiehorowski (1987, 300) found a “... near complete or total elimination of heel strike with higher heel lifts.” This is contrary to the clinical observation by Gastwirth et al. (1991) who found that frequent high heel wearers bear weight longer on their heels. More torsional movement of the ankle joint takes place in forefoot strikers (Stacoff, Källin, Stüssi, and Segesser, 1989) and can therefore not be compared to heel strikers on an equal basis. There is a danger in limiting subject parameters too much. It may limit the ability to generalize to the general high heel wearing public.

Training Sessions and Collection Preparation

Anyone who has ever attempted to walk or run on a treadmill knows that it is not as easy as it looks at first. When using a professional women’s group as a source for subjects, it cannot be expected that any of them are experienced treadmill walkers. This inexperience could result in rearfoot angle measurements which can be attributed to difficulties in walking on a treadmill rather than to the shoe conditions. To avoid this, training sessions or a habituation period is advisable. Several authors have stressed the
need for training sessions or at least an adequate warm-up to be able to ascertain meaningful data from treadmill studies. Many researchers used a warm-up period before testing subjects on the treadmill (Bates et al., 1979; Engsberg et al., 1987; Yamasaki et al., 1991; and Opila-Correia, 1990a) while others indicated the need to use training sessions (Hamill et al. 1992; Kernozek and Greer 1993; Kernozek and Ricard 1990; Mathews and Wooten 1963; and Van Woensel and Cavanagh 1992). In addition, Gastwirth et al. (1991) allowed no unaccustomed, strenuous activity two days prior to testing because muscle fatigue may affect rearfoot stability.

Footwear

Footwear can influence the outcome of a study in several ways. Often researchers are not careful in selecting footwear to match each other in all but the parameters studied. In addition, there is a chance that the order in which the test shoes are presented have an effect on the outcome of the study. Therefore, the choice of shoe type and random assignment are important considerations for a study on rearfoot stability.

Shoe Type.

A study dealing with assessments of different types of footwear immediately brings to mind potential problems in choosing the test shoes. Some researchers have not controlled the shoes used in their studies. Subjects provided their own running and high-heeled shoes for a study by Gehlsen, Braatz and Assmann (1986) and subject were allowed to determine what they considered to be an appropriate shoe for the categories given in a study by Soames and Evans (1987). This is not advisable because if subjects are allowed to use their own footwear, categories of shoe styles cannot be distinguished and uniformity of footwear cannot be guaranteed (DeLateur, Giaconi, Questad, Ko and Lehmann, 1991).
Random Assignment.

To avoid significant statistical differences between shoe conditions due to the order in which they were presented to the subjects, random assignment of the various styles of shoes to be worn by each subject is a consideration for researchers. Few of the studies reviewed here have given thought to this question. Only Clarke et al. (1983), Merrifield (1971) and Yamasaki et al. (1991) have used random assignment of shoe conditions to avoid any skewing of the data due to order of testing. Using random assignment is important when comparing different heel types to avoid the possibility that an effect can be attributed to the order in which the shoes were worn. Also, random assignment may increase the validity of the study’s findings.

Data Analysis

When analyzing the calculated rearfoot angles one or several footfall measurements (trials) are selected for each shoe type. The investigator cannot be sure that one trial selected would be the one best representing a typical trial for the subject. To avoid this pitfall, it is advisable to average several trials together and compare the averages for several footfalls in each of the different shoe styles. Bates, Osternig, Mason and James (1979) set up an experimental design to see if there is any significant difference between consecutive footfalls. They looked at three footfalls and found no significant difference between them. This means it should be acceptable to average several footfalls of the same subject. Others have also stressed the need for composite evaluation of several footfalls to test shoes (Clarke, Frederick and Hamill, 1983; Hamill, Bates and Holt, 1992; Kernozek and Greer, 1993; Soutas-Little, Beavis, Verstraete and Markus, 1987; Van Woensel and Cavanagh,
1992). Bates, Dufek and Davis (1992) recommended averaging at least three trials of biomechanical kinematic data in 20 subjects to get a statistical power beyond 90%.

Summary

Investigating rearfoot stability in high-heeled shoes is a complex problem. There are several aspects which have to be considered when studying rearfoot stability in high heels. One is the historical change and psychological factors behind the decision to wear high heels, another is the history of physiological research conducted on persons wearing high heels, and the last is the biomechanical research conducted with respect to rearfoot stability.

Fashion has a tendency to change but it never really changes too radically unless a radical upheaval occurs in society. During the French Revolution for example, the fashion of high-heeled shoes for men was abandoned entirely within a very short period. Generally, there have to be very compelling reasons for people to abandon a familiar clothing article entirely. This is true for women’s high heels. High heels have been criticized extensively, but women continue to wear them. Part of the reason may be the psychological connotations of high-heeled shoes. Although the psychological aspects will not be investigated in this study, the “feminine allure” of high heels may play a part in their continued existence. They also continue to be considered a necessary part of a woman’s career apparel.

Health issues involving high-heeled footwear have been investigated periodically for the past thirty years but not many of the results have brought about changes in the way high heels are designed. Studies have focused in particular on foot pressure and posture. Some investigations have dealt with oxygen consumption, gait angles and gait analysis. Many of the results are contradictory. This may be attributed to their relative spacing in time which may have brought about improvements in measuring techniques from one study to the next.
Over time, some general tendencies in statements about high-heeled shoes have emerged. High heels tend to move the center of gravity forward, flatten the lumbar spine, shorten the step length and increase step frequency. However, few studies examining the rearfoot stability of high-heeled shoes have been performed to date. It was therefore necessary to take a close look at investigative methods employed in rearfoot studies of running and tennis shoes. These studies provide a good foundation for an investigative study of heel stability in high-heeled dress shoes. Many of the methods used in the study of running shoes can be directly applied to the study of high-heeled shoes, the intended focus of the present study.
CHAPTER III

METHOD

Research Question

The purpose of this study was to compare rearfoot stability in the performance of women's high-heeled shoes with different heel dimensions. Three shoe styles were compared: flat shoes, high narrow heels and high broad heels (both high narrow and high broad heels were 2 1/2 inches in height). The shoes were of very similar upper construction. The relationships between heel height, shoe-to-ground contact area, and rearfoot angular stability in three different shoe styles were expected to be substantial.

Objectives of the Study

In order to achieve the purpose of this study, the following objectives were formulated:

1. To develop a procedure to compare the kinematic observations of rearfoot stability while walking on a treadmill in two high-heeled shoes with different heel types to that of walking in a flat shoe (this constitutes a total of three pairs of shoe styles) between subjects.

2. To compare the results of rearfoot angle measurements and the answers from the questionnaire for the three different shoe styles (two high heels and one flat).
Hypotheses

**Hypothesis 1:** There will be a difference between rearfoot stability in high heels and flat shoes.

a. There will be a difference between the maximum pronation angles in high heels and flat shoes.

b. There will be a difference between the minimum pronation angles in high heels and flat shoes.

c. There will be a difference between the pronation angles at heel strike in high heels and flat shoes.

d. There will be a difference between time to maximum pronation angles in high heels and flat shoes.

e. There will be a difference between time to minimum pronation angles in high heels and flat shoes.

f. There will be a difference between stance time in high heels and flat shoes.

g. There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the minimum pronation angle.

h. There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the pronation angle at heel strike.
**Hypothesis 2:** There will be a difference between rearfoot stability in high narrow heels and high broad heels.

a. There will be a difference between maximum pronation angles in high narrow heels and high broad heels.

b. There will be a difference between minimum pronation angles in high narrow heels and high broad heels.

c. There will be a difference between pronation angles at heel strike in high narrow heels and high broad heels.

d. There will be a difference between time to maximum pronation angles in high narrow heels and high broad heels.

e. There will be a difference between time to minimum pronation angles in high narrow heels and high broad heels.

f. There will be a difference between stance times in high narrow heels and high broad heels.

g. There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the minimum pronation angle.

h. There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the pronation angle at heel strike.

**Research Design**

The purpose of this study was to compare rearfoot stability in the performance of women's high-heeled shoes with different heel dimensions. The independent variables were the heel dimensions (combination of heel height and width) of the different shoe styles (shoe 1: flat shoe, shoe 2: high narrow-heeled shoe, and shoe 3: high broad-heeled
shoe). The dependent variables were the rearfoot angular range of motion using the maximum pronation angle minus the pronation angle at heelstrike (h), as well as the maximum pronation angle (a), minimum pronation angle (b), pronation angle at heel strike (c), time to maximum pronation angle (d), time to minimum pronation angle (e), stance time (f), and range of rearfoot motion using the maximum pronation angle minus the minimum pronation angle (g). A pilot test was conducted on a small sample of women to refine the questionnaire and data collection methods.

Data collection methods included the signing of the informed consent form and the completion of a questionnaire. A brief clinical assessment of each subject's feet was performed by David Lew, the former athletic trainer for the OSU women's basketball team. He had over twelve years of experience assessing athletic injuries and was therefore much better qualified to make a judgement about the foot health of the subjects than the investigator. Subjects tried on a range of shoe sizes of each shoe style to determine which would be the correct shoe size for each style. The shoes were presented to the subjects during the test in a crossover design. This means that the six possible orders of shoes were presented randomly to the first six subjects, the next six subjects and so forth. If there were 36 subjects, the design would be perfectly balanced. Rearfoot angles were calculated from data collected with the Qualisys® MacReflex data collection system while the subject walked on the treadmill (see page 65 for a description of the Qualisys® MacReflex system). Three infrared data collection cameras which were part of the Qualisys System and a Power Macintosh were used to film the 28 subjects at 60 Hz from about 5 degrees behind the left foot, about 45 degrees behind towards the left, and from about 85 degrees towards the left (see Figure 3.1). Digital data were immediately available to be converted and imported into the Excel Spreadsheet program. Because the data were relatively clean, there was no need to smooth it. Extensive manual calculation and transfer of the data were required to find all variables in the raw data and convert them into another spreadsheet which served as the source for statistical analysis. Relationships between variables were
analyzed using repeated measures Analysis of Variance and post hoc comparisons. Rearfoot angles of each of the three shoe styles were compared for the shoes overall as well as between the individual shoe styles.

Two factors to consider when undertaking a research study are reliability and validity. Reliability deals with the dependability of a certain indicator (in this study, the treadmill, the MacReflex system, the questionnaire, etc.). Validity shows the appropriateness of using certain indicators (in this case the measuring devices). It determines whether the instruments actually measure what they are supposed measure. The use of treadmills for the study of rearfoot stability is well established (Taves, Charteris and Wall, 1983; Lafortune et al., 1994) and can therefore be deemed reliable and valid. The use of the MacReflex System on the other hand is not quite as well established. Levy and Smith (1995) determined that the Qualisys® MacReflex System shows relatively small prediction errors for three-dimensional filming with three cameras using the small calibration structure provided by Qualisys®. Its reliability has not been demonstrated. Since the movements in this study were confined to the limits of this special calibration structure (a frame with nine reflective reference markers) it is assumed that it is reliable and valid within the limitations outlined by Levy and Smith (1995). The reliability and validity of the questionnaire were not ascertained. A pilot test established that the measurement tools worked well together.

Population

When studying running shoes, researchers typically use either athlete and/or recreational runners, depending on the market segment for which the shoes are aimed. When studying high-heeled shoes, it is similarly important to select a sample of subjects who are accustomed to wearing high-heeled shoes. It is for women who regularly wear
high-heeled shoes and the manufacturers targeting this group that the results of this study will have the most meaning.

The population used in this study was from the Corvallis, Oregon business community. They were women between the ages of 24 and 54 who worked in office environments and were expected to wear high-heeled shoes to work frequently. They worked in offices of different sizes and most women had to walk in their heels for various distances every day. All women had been wearing high-heeled shoes for at least 16 hours a week for the past year, but many had been wearing them a lot more frequently. This population could be considered experienced high heel wearers (refer to Appendix A for the screening questionnaire).

Subjects

In the following section, sample selection, subject parameters, and the importance of informed consent are described. Since instability in wearing high-heeled shoes could easily be attributed to inexperience, injury, or some other factor, careful choice of subjects is pertinent.

Sample Selection

Many women wear high-heeled shoes occasionally. When studying the effects of high heels, it is critical to select a sample of women who wear them regularly. The most expedient way to obtain a sample of such women would seem to be to contact a group of professional women. Originally, the subjects for this study were to be volunteers recruited from one of several women's professional groups. However, this proved to be difficult in
Corvallis. Therefore, subjects were recruited from offices and businesses around town which were canvassed by the investigator. Subjects were questioned before they were accepted for participation to make sure they wore high heels at least two to three days a week for the entire work day (8 hours or more). Gastwirth et al. (1991, 470) postulated that "...gait adaptations are suggestive of a learned locomotor response to wearing high heels." The use of experienced subjects in this study should avoid confounding effects due to inexperience.

Another important aspect about the subjects was their age. Murray, Kory, and Sepic (1970) found strong age-related gait differences in subjects 60 and older and some differences in subjects 50 and older. Opila-Correia (1990b) also found differences among subjects of different age levels or experience levels when walking in high heeled shoes. Age of subjects was therefore limited to those over 20 and under 55 years of age. Subject age range was also limited to avoid changes in bone and ligament structure due to menopause affecting rearfoot stability.

**Subject Parameters**

For the purpose of statistical analysis (balanced crossover design), the number of subjects was planned to be a multiple of six. However, due to the drop-out of some subjects, this was not possible. The sample consisted of twenty-eight (28) non-pregnant, healthy women approximately 24-54 years of age (the desired range was 20-54), between 5'0" and 5'10 1/2" tall (the desired range was 5'0"-5'10"), weighing between 115 and 185 pounds (the desired range was 100-200), and wearing a shoe size between 6 and 9 (the desired range was the same). The weight range was limited to exclude grossly overweight or underweight persons because Kinoshita, Ikuta, and Okada (1990) found significant interaction between body weight and a tendency to pronate.
Shoe size was limited for several reasons. There may be large variation in the fit of the shoes due to differences in construction at the extremes of the size range. Shoe companies often do not size shoes proportionally, using the same heel for a size 5 that is used for a size 11. In addition, the cost of buying three pairs of shoes for a large size range was too costly for a student project. Therefore, the most commonly worn sizes (6, 6 1/2, 7, 7 1/2, 8, 8 1/2, and 9) were selected for this study. Also due to cost constraints, only 'B' width (average) shoes were purchased for this study.

Subjects who exhibited lasting effects from previous injuries were excluded from the present study during the screening process. Subjects were interviewed either in person or over the phone to see if they wore high heels often enough (at least 16 hours a week for the past year), and if age, shoe size and width, height, and weight were within the parameters set. Previous studies have shown the benefit of limiting subject parameters (Merrifield, 1971). It is felt that the range of subjects allowed in this study was broad enough to draw valid conclusions without being too broad (increased variability due to a subject's age, height, weight, shoe size or previous injuries).

Informed Consent

Human subjects participating in research projects at Oregon State University are required to sign an informed consent form which explains the nature of the research project to them. In the informed consent form for this study (Appendix B), possible risks and benefits were outlined. It promised that their names would be kept confidential and that results from the study would only be used for research relating to rearfoot stability of high-heeled shoes. They received the name and telephone number of the investigator to ensure a means of contact if they had questions. Subjects were informed that their participation was voluntary, and they could cease participation at any time for any reason. It is customary to
obtain an informed consent form from subjects to ensure their protection as well as that of
the researcher and the institution.

Instruments

The following section examines the different instruments used to test the hypotheses
put forth for this thesis. It describes the questionnaire, the clinical assessment, the footwear
used, the treadmill, the use of random assignment, and the kinematic analysis system.

Questionnaire

A questionnaire (see Appendix C) was developed as an aid to interpret the findings of
the kinematic study. There was the possibility that outliers which seemed significant could
have appeared in the data set. These outliers might have been explained by cross-
examination with the answers given in the questionnaire. For example, one such subject
may not wear high-heeled shoes as regularly as others.

Assessment of Foot Parameters

After subjects completed the questionnaire, they were given a brief clinical assessment
(for the assessment form see Appendix D). The assessment was designed to ascertain
whether any subjects had foot or gait abnormalities, in which case they would be eliminated
from the study. One subject was allowed to participate in the study although the assessment
process indicated that she did not have as much ankle stability as the rest of the group.
However, her moderate ankle laxity could not be considered grossly abnormal.
A question on the questionnaire determined whether subjects were right-handed or left-handed. The answer for this question was double-checked during the clinical assessment. A majority of the subjects were expected to exhibit smaller foot angles with their left foot than their right foot as determined by several previous studies (Kernozek and Ricard, 1990; Van Woensel and Cavanagh, 1992). Therefore, only the left leg and foot were chosen for data collection. The amount of toeout with respect to the midline was noted for each subject (with the help of a reflective marker on the medial border of the second toe of the subject). This value was used to calculate the rearfoot angles corrected for the individual toeout of each subject. Although the data collection used three-dimensional analysis, this further reduced the possibility for error.

Footwear

The following section will discuss uniformity and fit of footwear used in this study.

Uniformity

This study used three different shoe styles, a flat shoe purchased at Volume Shoe Source, a high broad-heeled shoe purchased at Picway Shoes, and a high narrow-heeled shoe purchased at Volume Shoe Source. Although the names of the two shoe stores are different, they are owned by the same company, and the shoes may well have been made by the same manufacturer. As of October, 1994, the names of Volume Shoe Source and Picway Shoes have been changed to Payless Shoes after a dispute about the name with Payless Drug Stores was settled (Footwear News, 1994). Numerous researchers have stated that results of their studies on high-heeled footwear were influenced by the variability in the footwear used (Gehlsen et al., 1986; Merrifield, 1971; Opila-Correia 1990a; Soames
and Evans, 1987). Therefore, all three shoe styles used in this study were carefully selected so that they differed only with respect to the shape and height of the heel but not with respect to any other parameters. All shoes were of medium width (B), and all shoes were manufactured in China. The heel height of the flat shoes in this study was three-eighth inch, and the high heels were two-and-one-half inches in height, height referring to the difference between the plane under the metatarsal-phalangeal joint and the plane under the calcaneous (ball of the foot and heel of the foot).

**Fit of Sample Shoes.**

The lateral rearfoot motion of running shoes adds about two to three degrees to the total rearfoot motion of a subject’s foot, more or less depending on the fit of the individual shoe (Stacoff, Reinschmidt, and Stüssi, 1992). One would think that this could be controlled by lacing the shoes more tightly, but that is not necessarily the case. Sometimes shoes do not fit the foot type well enough to allow for such an adjustment. All subjects in this study indicated they wore B width shoes, the width of the test shoes, to ensure proper fit with regard to width.

Women's dress shoes have less movement of the foot within the shoe because their heels usually fit more tightly than those in running shoes. In addition, some women have a tendency to wear dress shoes which are too small for them (Frey, et.al., 1993). This further reduces the movement of the heel within the shoe. The importance of a good shoe fit has been stressed by Clarke et al. (1984), Mathews and Wooten (1963), and Merrifield (1971). In this study, a good fit (not too tight or too loose) was ensured to gain a reasonable representation of rearfoot movement as measured by the markers on the heel counter. Shoe fit was assessed, and the size required for each individual style was used.
Treadmill

The treadmill used in this study was manufactured by Quinton®. It had variable speed and inclination and a rubber revolving walkway. The advantage of using a treadmill rather than an overground walkway (usually a certain area and distance marked off in the data collection room) is that speed is easily controlled. The subject stays reasonably stationary while simulating the movement of normal gait. Taves, Charteris, and Wall (1983) contended that after a training or a habituation period the differences between treadmill and overground walking are small. Lafortune, Hennig, and Milani (1994) also found little difference between treadmill and overground walking with regard to pronation.

Some may question the soundness of using a treadmill for assessing rearfoot stability, but the convenience and the ability to exactly repeat methods outweighs the aim to replicate real life conditions. In addition, subjects performed all walking trials on the same treadmill. Treadmills have been used commonly and successfully in rearfoot running observations. All subjects were tested at the same speed of two miles per hour.

Random Assignment

The order in which subjects wore the different shoe styles was randomly assigned. Clarke et al. (1983), Merrifield (1971) and Yamasaki et al. (1991) also used random assignment, and Hamill et al. (1992) and Van Woensel and Cavanagh (1992) counterbalanced their testing conditions. This means they varied the order in which shoe styles were worn by subjects according to some predetermined pattern.

In this study, the pattern of random assignment of the shoe styles was determined before testing took place. There were six different ways in which the tested shoe styles could be combined. This meant that each pattern was represented four or five times but the
order in which they were presented to the subjects was randomized. Subjects also appeared in a random order for their test appointments.

**Kinematic Analysis System**

The kinematic analysis system used in this study was the Qualisys® MacReflex Data Analysis System for the Macintosh computer. It uses either three (up to 60 Hz) or six (120 Hz) infrared cameras which record and allow immediate access to 3D digital data. Previous studies have used video cameras to collect rearfoot kinematic data. Complicated movements such as high speed or twisting movements have used 16mm film cameras (such as a Locam®) or video cameras that record at a higher frame rate. Both of these systems require lengthy digitizing of data after filming. This creates the strong possibility of introducing some error during manual digitizing. The Qualisys® MacReflex System was chosen after pre-testing revealed that it was well suited for this type of movement (the subject's movement occurs in a relatively straight line, with little twisting, at a moderate speed, and in a confined area). Levy and Smith (1995) determined that the Qualisys® MacReflex System works best for movements that are confined to the limits of the special calibration structure (a frame with nine reflective reference markers) provided by Qualisys®. Measuring rearfoot movement is well-suited to the Qualisys® MacReflex system.

Three cameras were used to provide three-dimensional data. When filming moving subjects, it is important that no more than a few of the markers on the body will be hidden from view for more than a few film frames. Therefore, careful camera placement was crucial for this study. Because the angles measured were relatively small, and thus any variation was important, using this three-dimensional setup improved the reliability of the measured angles. The Qualisys® MacReflex system provided relatively clean data, so that it was possible to execute the angle calculations from raw data. No smoothing was
necessary. Smoothing is a mathematical treatment of data that eliminates extraneous noise. Noise in data refers to slight deviations from the true measurements. The true measurements can be approximated by several interpolation or smoothing techniques.

Subjects were filmed for ten seconds in each shoe style after adjusting their gait to the treadmill for about five minutes each. Adjustment was considered to have taken place when the subject was able to walk comfortably within the same area on the treadmill, that is, when their movement towards the front, the back, or the sides of the treadmill was minimal. Tape on the floor marked the camera positions to ensure consistency between subjects.

The calibration structure was used during each collection period to avoid the introduction of errors by a third party moving any of the equipment. Cameras were placed 5 degrees behind, 45 degrees behind and to the left, and to the left (about 85 degrees) of the treadmill (see Figure 3.1). Filming speed was 60 Hz. After each subject adjusted to walking on the treadmill (that is, when she walked within the same area of the treadmill and indicated feeling comfortable), she was filmed in each of the three shoe styles. Five consecutive foot strikes were later analyzed.
Figure 3.1: Camera setup relative to the treadmill
Data Collection Method

A pilot test was conducted to ensure the method proposed could be used with confidence by the researcher and to ensure that the measurement tools would be properly used. Two subjects were tested using the Qualisys® MacReflex Data Collection System prior to the actual study.

Collection Preparation

After completing the informed consent form (required by Oregon State University, Appendix D), subjects were asked to complete the questionnaire. Subsequently, a brief clinical assessment of their feet was conducted by David Lew (athletic trainer). A data collection sheet was completed by the trainer for each subject and attached to the questionnaire completed by the subject. Foot shapes, ankle tests, foot dominance, and arch height were tested and noted.

Training Session

Subjects were given the opportunity to take part in a training session during their first appointment in the Biomechanics Lab at Oregon State University. They were given up to fifteen minutes to practice getting on and off the treadmill in their own shoes. Some subjects regularly work out on treadmills and therefore did not need to practice at this time. Subjects had time to think about walking on the treadmill for a few days between practice and the actual filming. Imagining a task after doing it often improves the performance of this task the next time it is performed. During the next data collection session, subjects were allowed to practice walking on the treadmill again in each pair of shoes until they
communicated to the researcher that they felt comfortable. They were given a period of habituation of two to fifteen minutes before filming took place to become accustomed to walking on this particular treadmill. Then the data were collected.

Kinematic Data Collection

In order to obtain the desired data, a three-dimensional kinematic approach involving three infrared film cameras was used. Rather than using film, these cameras immediately converted the collected data to digital coordinates. Test subjects walked on the treadmill while they were being filmed simultaneously 1) from the rear, 2) about 45 degrees behind and towards the left, and 3) a left side view. Subjects were fitted with small reflective markers (reference markers, 5/16” [0.7cm] diameter) on their legs and shoes. They were placed on the lower edge of the back of the heel of the shoe and at the top of the rear shoe seam. Shoes were prepared before subjects came in for testing. On the subject, markers were placed on the Achilles tendon and on the line extending from the Achilles tendon to just below the belly of the gastrocnemius (calf muscle, see Figure 3.2). Following Clarke's methods during the extensive pilot trials provided the experience to palpate the Achilles tendon and the dimple created by it below the gastrocnemius in most subjects during the trial. A measuring tape was substituted for the device used by Clarke et al. (1983, 1984). During the pilot test, the reliability of marker placement was found to be satisfactory. Clarke et al. (1983, 1984) and Luethi et al. (1986) also used methods to ensure reliable marker placement.
In video taping the legs, wearing dark pantyhose increases the visibility of the markers but with infrared cameras dark hose are not necessary. However, the markers are more easily removed from hose than from the leg. The markers on the leg were placed over pantyhose in this study. Reflective markers were successfully used by Beuter and Duda (1985), Hamill, Bates, and Holt (1992), and Murray, Kory, and Sepic (1970). If the pixel
dimensions are too large, it is hard to determine where in the pixel space the reflective marker is located. During the development of this method, the ideal resolution of the reflective marker size was found to be very small (to accurately represent the body landmark), but not too small (to still be distinguished from the surrounding area by the cameras). The marker size chosen was a cylinder of 5/16" [7-8 mm] in diameter and 1/4" [6 mm] in height wrapped with reflective tape. Double-stick tape was used to adhere the marker to the shoes and leg.

Subjects were asked to walk at a set speed on the treadmill (2 miles per hour or 0.88 m/s). Soames and Richardson (1983) recommended confining the speed to certain limits. Gastwirth et al. (1991) found no cadence differences between barefoot, low heel, and high heel styles. Therefore cadence was not controlled. Each subject was filmed three times for ten seconds each.

Following the suggestion by Lee, Matteliano, Medige, and Smiehorowski (1987), three posters were mounted about 5' - 6'7" [1.5-2m] high on the wall in front of the subjects. They served as a visual cue to help subjects look straight ahead. In addition to focusing the subject’s attention, reflex performance at the ankle increases with the use of visual cues upon which subjects can focus (Fitzpatrick, Taylor, and McCloskey, 1992). It gives subjects a perception of the distance ahead which makes it easier for them to walk more steadily in the same area of the treadmill. Franklin, Chenier, Brauninger, Cook, and Harris (1995) also used visual cues mounted on a wall to help the subjects in their investigation of the effect of high heels on posture focus and reduce postural sway.

Questionnaire

As mentioned previously, the questionnaire (Appendix C) was designed to find alternative explanations in the event that there were large differences or no differences
between the variables investigated. For example, there could be external factors which account for discrepancies not obvious from the laboratory tests. The responses to specific questions from all of the subjects were compared to the laboratory results using a correlation matrix. The questions analyzed for comparison to the laboratory data included age, height, weight, foot and hand dominance, shoe sizes (measured versus self-reported versus worn during the laboratory tests) shoe widths, number of broad and narrow high heels owned, number of medium heels owned, times worn per week and if so, all day, half day, or as little as possible.

Data Analysis

To reduce the chance of any data error due to subject variability, several (five) footfalls of the left foot were averaged together to characterize and compare each of the different shoe styles. Bates, Osternig, Mason, and James (1979) set up an experimental design to determine if there was any significant difference between consecutive footfalls. They compared three footfalls of the same subject and found no significant difference between them. Others have also stressed the need for the composite evaluation of several footfalls in test shoes (Clarke, Frederick, and Hamill, 1983; Hamill, Bates, and Holt, 1992; Kernozek and Greer, 1993; Soutas-Little, Beavis, Verstraete, and Markus, 1987; Van Woensel and Cavanagh, 1992). Bates, Dufek, and Davis (1992) recommended averaging at least three trials of biomechanical kinematic data (this recommendation refers to any biomechanical measurements) in at least 20 subjects to get statistical power (reliability) above 90%. In this study, five footfalls were averaged to get one value for each subject.
Statistical Tests

In order for data to be interpreted, comparisons are made between variables tested. Statistical analysis is a method used to show if there are significant relationships between the independent variables tested. The descriptor of the center of gravity of repeated measures is given by the mean. The relative spread about the mean is given by the variance. The variance is a measure of the statistical variability in the data. The larger the variability about the mean, the larger the variance. The single factor analysis of variance (ANOVA) is a statistical test that allows the comparison of several independent means or averages (Devore and Peck, 1986). The objective is to test whether several means are different based on certain assumptions about their distribution. Here it is assumed that the measurements are normally distributed. Under a normal distribution, data from repeated measurements will, on average, fall to within a certain statistical distance from the mean. On the one hand, if the difference between the means of several observations is small, it is assumed to be due to sampling variability. In this case, the means are said to be statistically similar. On the other hand, if the difference between the means is large, alternative explanations are required to describe the discrepancy. Specifically, the test which will be used as the test statistic is called a single factor ANOVA F-test. The F-test provides a way to calculate the relative discrepancy between several means. The F-test is the ratio between means and allows the comparison of the means weighted against the measure of the combined variability of the means (appendix E).

Using the ANOVA test, eight variables were used to study shoe rearfoot stability: maximum pronation angle (1), minimum pronation angle (2), pronation angle at heel strike (3), time to maximum pronation angle (4), time to minimum pronation angle (5), total stance time (6), range of pronation using maximum pronation minus minimum pronation (7), and range of pronation using maximum pronation minus pronation at heelstrike (8). All variables were tested using the same three shoe styles under similar laboratory conditions.
as described earlier. Most of these variables were chosen because they are recognized as a measure of the degree of shoe stability in high heels (Ebbeling et al., 1994; Hontalas and Williams, 1995; Snow and Williams, 1994). The statistical software used to determine if there was a difference between the means of all shoes was StatView for the Macintosh. Post hoc comparisons were used to determine if there were significant statistical differences between the means of the individual shoes tested. Contrasting the means of the three shoe styles allowed the researcher to make more confident statements about which shoe style provided more rearfoot stability. The statistical package used for these tests was SuperANOVA for the Macintosh.

Summary

The method used in this study is well suited to answer the question of whether flat shoes, high heels with a narrow heel, or high heels with a broad heel provide more stability when walking. Filming subjects from behind, a semi-side, and a side view with the Qualisys MacReflex Data Collection System while they walked on a treadmill with reflective markers representing the axes of the leg and the foot is a useful way to collect rearfoot data. Coordinate values with which rearfoot angles could be calculated were available immediately. The results were used to compare the three different shoe styles to each other with regard to rearfoot movement, the subjects to each other with regard to rearfoot movement, and the subjects’ answers on the questionnaire to their rearfoot movement as distinct groups. Many researchers have previously used similar methods to investigate rearfoot stability in running shoes with good results. Very few researchers have used similar methods to investigate rearfoot stability in high-heeled shoes.
CHAPTER IV

RESULTS

The purpose of this study was to compare rearfoot stability in the performance of women’s high-heeled shoes with different heel dimensions. To do this, the relationship between heel height, shoe-to-ground contact area, and rearfoot angular stability in three different shoe styles (a flat shoe, a high narrow-heeled shoe, and a high broad-heeled shoe) were investigated. Three dimensional kinematic data analysis using the Qualisys® MacReflex Data Analysis System was used to calculate the rearfoot angles for each subject for five consecutive left foot strides. The measured variables included Maximum Pronation, Minimum Pronation, Pronation at Heel Strike, Time to Maximum Pronation, Time to Minimum Pronation, Stance Time, and Range of Pronation using both the Maximum Pronation minus the Minimum Pronation as well as the Maximum Pronation minus the Pronation at Heel Strike.

Objectives of the Study

In order to achieve the purpose of this study, the following objectives were formulated:

1. To develop a procedure to compare the kinematic observations of rearfoot stability while walking on a treadmill in two high-heeled shoes to different heel types with that of walking in a flat shoe (this constitutes a total of three pairs of shoe styles) between subjects.
To compare the results of rearfoot angle measurements and the answers from the questionnaire for the three different types of shoe styles (two high heels and one flat).

**Anthropometric Data**

To make sure the subjects in this study conformed to certain parameters, three instruments were used. The screening questionnaire was used to eliminate unsuitable subjects, the clinical assessment provided additional information about subjects’ foot and ankle stability, and the questionnaire verified that subjects conformed to the research parameters and showed possible correlations with the kinematic results.

**Subject Parameters set forth in the Candidate Screening Questionnaire**

The twenty-eight (28) subjects who participated in this study were female volunteers recruited from the business community in Corvallis, Oregon. They were selected from over 100 women contacted prior to data collection. Subjects had to conform to certain parameters to be admitted to the study. They had to have worn high-heeled shoes of at least one inch or more for two to three days a week (or 16-24 hours a week) for the past year, their shoe size had to be between 6 and 9 and of medium width, their age had to be between 20 and 54, their height between 5 foot and 5’10 inches, their weight between 100 and 200 pounds, and they could not have had any significant ankle injuries in the five years prior to this study (see screening questionnaire in Appendix A).
Physical Assessment Results

Human foot shapes can be classified into three main groups. They are an Egyptian foot shape with a prominent first digit (big toe), a Greek foot shape with a prominent second digit (second toe), and a square foot shape with equally long first and second digit (big and second toe are almost the same). The physical assessments of all subjects resulted in 10 women with a Greek, 9 women with an Egyptian, and 9 women with a square foot shape. This is somewhat surprising because Magee (1992) reported that the Egyptian foot occurs most often (69%), the Greek foot second most (22%), and the square foot the least common (9%) in the general population. It appears that the study he quoted originated in Barcelona, Spain, which may account for the difference of this study. Forty-three percent of the women (12) had minor foot or ankle problems. Only one displayed a less than solid left ankle. The problems observed included mild popping, tenderness, slight laxity, mild crepitus (a sound made by, for example, tendons slipping over bone), and slight joint grinding. Foot dominance was determined by having subjects pretend they were to kick a ball really hard. The athletic trainer observed and recorded the foot used. In the questionnaire they were asked to think if they had to hop on one foot, which one it would be. Twenty-five subjects showed a right-foot dominance, two showed a left-foot dominance, and one was ambidextrous. The clinical assessment determination for this parameter matched the self-reported foot dominance in the questionnaire. The ambidextrous woman and the two women with a left foot dominance showed the same pattern for handedness. Two of the group with right-foot dominance were left-handed.

In this study, the left foot was observed because Matsusaka, Fujita, Hamamura, Norimatsu, and Suzuki (1983) stated that the side of the dominant leg is usually opposite to the dominant arm. This is not consistent with the findings in this study and the findings of the gait laboratory at Shriner’s Children’s Hospital in Portland, Oregon (M. Orendurff,
According to Orendurff, most persons are right-handed and right-footed. The results of the clinical assessment and questionnaire of this study also indicated a dominant right foot for most subjects, i.e. same hand and foot dominance. For the detailed clinical assessment form refer to Appendix D.

Subject Questionnaire Results

The questionnaire (Appendix C) revealed information that aided in interpreting the kinematic data. The actual mean physical characteristics of all women are summarized in Tables E.1, E.2, and E.3 (Appendix E). The mean age of all women was 37.5 years with a standard deviation of 9.5 years. Their average height was 64.6 inches (SD = 2.7 inches) and their average weight was 146 pounds (SD = 25 pounds). They wore high heels for an average of 3.6 (SD = 1.7) days a week. The mean shoe size of all subjects was 7 1/2 (SD = 1). All subjects walked or ran for exercise, indicating no lack of inherent ankle stability due to muscle tone. Sixteen subjects walked or ran an average of less than seven (7) miles per week, eleven walked or ran seven to fourteen (7-14) miles per week, and one subject ran fourteen to twenty-one (14-21) miles per week. All also communicated that they had to walk a fair amount in heels and were able to walk comfortably at the preset speed of 2 miles per hour (0.88 m/s) in high heels on the treadmill.

Statistical analysis showed that subjects in this study tended to wear a whole shoe size larger in fashion shoes (narrow toe box) than their measurements with a Brannock® device would suggest. Older subjects tended to own more high-heeled shoes and wore them more often and longer than younger subjects. This may have been due to consumer trends.

To determine if there was a linear correlation between any of the questions on the questionnaire and the kinematic data, the eight rearfoot stability variables (maximum pronation, minimum pronation, pronation at heel strike, time to maximum pronation, time
to minimum pronation, stance time, range of pronation using maximum pronation minus minimum pronation, and the range of pronation using maximum pronation minus the pronation at heel strike) and the variables from the questionnaire (age, height, weight, shoe sizes [measured, worn in this study and self-reported], shoe widths [measured], and number of high heels owned by the subject and number of times high heels are worn per week) were examined in a correlation matrix. High correlation was determined to be a value of at least 0.8 and high inverse correlation was determined to be a value of at least -0.8. The results of the matrix revealed that none of the kinematic and questionnaire variables were highly correlated. The highest correlation value was +0.42, with most others below ±0.2. The comparison of some answers from the questionnaire with the rearfoot angle measurements fulfilled objective 2: To compare the results of rearfoot angle measurements and the answers from the questionnaire for the three different types of shoe styles (two high heels and one flat).

Statistical Data Analysis

The data of this study were analyzed using a repeated measures analysis of variance (ANOVA) for each of the dependent variables tested (Maximum Pronation, Minimum Pronation, Pronation at Heel Strike, Time to Maximum Pronation, Time to Minimum Pronation, Stance Time, and Range of Pronation using both the Maximum Pronation minus the Minimum Pronation as well as the Maximum Pronation minus the Pronation at Heel Strike). Measuring and analyzing the results fulfilled objective 1: To develop a procedure to compare the kinematic observations of rear-foot stability while walking on a treadmill in two high-heeled shoes with different heel types with that of walking in a flat shoe (this constitutes a total of three pairs of shoe styles) between subjects. The ANOVA for each independent variable (flat shoe—1, high narrow heel—2, and high broad heel—3) was calculated. Post hoc analyses served to compare the differences between the means of the
individual shoe styles to each other. Based on the results obtained, four subhypotheses of Hypothesis 1 proposed in Chapter 1 were accepted (Pronation at Heel strike, Time to Maximum, Time to Minimum, and Range of Motion using Maximum Pronation minus Pronation at Heel strike) while the others were rejected. Of Hypothesis 2, five hypotheses were accepted (Maximum Pronation, Minimum Pronation, Pronation at Heel strike, Time to Minimum Pronation, and Stance Time) whereas the other three were rejected.

Repeated Measures ANOVA

The objective of using a repeated measures ANOVA was to determine whether difference in mean values was attributable to general variability among all subjects when wearing a particular shoe style or to significant differences between the means of the values derived for those shoe styles. An ANOVA allows the comparison of several independent means or averages (Devore & Peck, 1986). Data from repeated measurements will, on average, fall to within a certain statistical distance from the mean. If the difference between the means of several observations is small, it is assumed to be due to sampling variability. If the difference between the means is large, alternative explanations are required to describe the discrepancy.

To aid in determining whether the difference between two means is significant, two additional values are generally used. They are the $p$ and the $F$. The F-test provides a way to calculate the relative discrepancy between several means. The F-test is the ratio between means and allows the comparison of the means weighted against the measure of their combined variability (Devore & Peck, 1986). The $\alpha$-level is the smallest level of significance at which the Null-Hypothesis could be rejected (Devore & Peck, 1986). The $F$ is related to the $\alpha$-level. It is derived by determining the F-ratio. The F-ratio is the ratio of the degrees of freedom of the numerator related to the degrees of freedom of the
denominator. This ratio can be used to determine the $F$ at which the difference between two means becomes significant as it relates to a chosen $\alpha$–level. A limiting $\alpha$–level of .05 or .01 can be chosen. If an $\alpha$–level of .01 is chosen, one can be a little more confident that there is a significant difference between the means than if a $\alpha$–level of .05 is chosen. For this study the degrees of freedom for the numerator are 2 and those for the denominator are 27. Therefore, at an $\alpha$–level of .05 the $F$ would be 3.35 and at a $\alpha$–level of .01, the $F$ would be 5.49. If the $F$ reported is larger than these numbers, the means are significantly different. The larger it is, the more confident one can be. In the following discussion, the individual results of each dependent variable with respect to the independent variables (shoe styles) are discussed and their $\alpha$–levels and $F$s are reported.

Rearfoot Angles

In the following section, the angles measured in this study will be discussed. They are maximum pronation, minimum pronation, and pronation at heelstrike. Figure 4.1 shows two examples of rearfoot angles for two subjects. The data were reasonably clean, so that no smoothing was performed.
Figure 4.1: Typical rearfoot angles during stance for two different subjects in flat shoes.
Maximum Pronation Angles

Subhypothesis 1a states: *There will be a difference between maximum pronation angles in high heels and flat shoes*. Maximum pronation is the value of the greatest overall rearfoot angle during the stance phase. As shown in Table 4.1, the maximum rearfoot angles measured during the entire stance phase of all 28 women were significantly different for the high narrow-heeled shoe (mean = 11.6 degrees) compared to the high broad-heeled shoe (mean = 8.8 degrees). The flat shoe (mean = 11.9 degrees) was significantly different compared to the high broad-heeled shoe (mean = 8.8 degrees, overall $F = 16.0$ and overall $p < .0001$). Post hoc analysis revealed there was no significant difference between the flat shoe (mean = 11.9 degrees) and the high narrow heel (mean = 11.6, $F = .164$ and $p = .6875$). Subhypothesis 1a was rejected. On the other hand, subhypothesis 2a: *There will be a difference between maximum pronation angles in high narrow heels and high broad heels*, was accepted. There was a significant difference between the means of the flat shoe (mean = 11.9 degrees) and the high broad heel (mean = 8.8 degrees, $F = 25.9$ and $p < .0001$) and the high narrow heel (mean = 11.6 degrees) and the high broad heel (mean = 8.8 degrees, $F = 22.0$ and $p = .0001$).
Table 4.1: Summary of Mean Maximum Pronation Angles in Degrees

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects</td>
<td>11.9 (3.1)*</td>
<td>11.6 (4.7)*</td>
<td>8.8 (3.7)*</td>
<td>16.0</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Differences (1,2)</td>
<td>vs. narrow</td>
<td></td>
<td></td>
<td>0.16</td>
<td>.6875</td>
</tr>
<tr>
<td>Differences (2,3)</td>
<td></td>
<td>vs. broad</td>
<td></td>
<td>22.0</td>
<td>.0001</td>
</tr>
<tr>
<td>Differences (1,3)</td>
<td></td>
<td></td>
<td>vs. flat</td>
<td>25.9</td>
<td>.0001</td>
</tr>
</tbody>
</table>

*= standard deviation

Minimum Pronation Angles

Subhypothesis 1b states: *There will be a difference between minimum pronation angles in high heels and flat shoes.* As shown in Table 4.2, the results for the minimum rearfoot angles measured during the entire stance phase of all 28 women mirrored those of the maximum rearfoot angles. The angles were significantly different for the high narrow-heeled shoe (mean = 3.6 degrees) compared to the high broad-heeled shoe (mean = 1.6 degrees) and the flat shoe (mean = 3.8 degrees) compared to the high broad-heeled shoe (mean = 1.6 degrees), but not for the high narrow-heeled shoe (mean = 3.6 degrees) compared to the flat shoe (mean = 3.8 degrees, overall F = 10.1 and overall p = .0002). There was no significant difference between the means of the flat shoe (mean = 3.8 degrees) and the high narrow heel (mean = 3.6 degrees, F = .22 and p = .6379).

Subhypothesis 1b was rejected. Subhypothesis 2b states: *There will be a difference between minimum pronation angles in high narrow heels and high broad heels.* It was accepted because there was a significant difference between the means of the narrow high heel (mean = 3.6 degrees) and the high broad heel (mean = 1.6 degrees, F = 13.2 and p = .0006).
Table 4.2: Summary of Mean Minimum Pronation Angles in Degrees

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects</td>
<td>3.8 (3.6)*</td>
<td>3.6 (3.6)*</td>
<td>1.6 (3.4)*</td>
<td>10.1</td>
<td>.0002</td>
</tr>
<tr>
<td>Differences (1,2)</td>
<td>vs. narrow</td>
<td></td>
<td></td>
<td>0.22</td>
<td>.6379</td>
</tr>
<tr>
<td>Differences (2,3)</td>
<td></td>
<td>vs. broad</td>
<td></td>
<td>13.2</td>
<td>.0006</td>
</tr>
<tr>
<td>Differences (1,3)</td>
<td></td>
<td>vs. flat</td>
<td></td>
<td>16.9</td>
<td>.0001</td>
</tr>
</tbody>
</table>

* = standard deviation

Pronation Angles at Heel Strike

Subhypothesis 1c states: *There will be a difference between pronation angles at heel strike in high heels and flat shoes.* As shown in Table 4.3, there was a significant difference between the rearfoot angles of all three shoe styles for pronation at heel strike. The results for the rearfoot angles at heel strike measured during the entire stance phase of all 28 women were significantly different for the high narrow-heeled shoe (mean = 4.9 degrees) compared to the high broad-heeled shoe (mean = 2.8 degrees) and the flat shoe (mean = 7.9 degrees) compared to the high broad-heeled shoe (mean = 2.8 degrees), as well as the high narrow-heeled (mean = 4.9 degrees) shoe compared to the flat shoe (overall F = 50.6 and overall p < .0001). For the means of the flat shoe (mean = 7.9 degrees) and the high narrow heel (mean = 4.9 degrees, F = 34.8 and p .0001), as well as between the means of the flat shoe (mean = 7.9 degrees) and the broad high heel (mean = 2.8 degrees, F = 100.1 and p .0001) there was a significant difference. Subhypothesis 2c states: *There will be a difference between pronation angles in high narrow heels and high broad heels.* Indeed, the means of the high narrow heel (mean = 4.9 degrees) and the
broad high heel (mean = 2.8 degrees) showed a significant difference. ($F = 16.9$ and $p = .0001$). Both subhypotheses were accepted.

**Table 4.3: Summary of Mean Pronation Angles at Heel Strike in Degrees**

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects</td>
<td>7.9 (3.7)*</td>
<td>4.9 (3.4)*</td>
<td>2.8 (3.7)*</td>
<td>50.6</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Differences (1,2) vs. narrow</td>
<td></td>
<td></td>
<td></td>
<td>34.8</td>
<td>.0001</td>
</tr>
<tr>
<td>Differences (2,3) vs. broad</td>
<td></td>
<td></td>
<td></td>
<td>16.9</td>
<td>.0001</td>
</tr>
<tr>
<td>Differences (1,3) vs. flat</td>
<td></td>
<td></td>
<td></td>
<td>100.1</td>
<td>.0001</td>
</tr>
</tbody>
</table>

* = standard deviation

**Temporal Aspects**

In the following section, the temporal aspects of rearfoot stability measured in this study will be discussed. They are time to maximum pronation, time to minimum pronation, and stance time.

**Time to Maximum Pronation Angles**

Subhypothesis 1d states: *There will be a difference between time to maximum pronation angles in high heels and flat shoes.* Table 4.4 summarizes the results for time to maximum rearfoot pronation in seconds. The time it took for subjects to reach maximum pronation was not significant. However, it showed a different pattern than that of the maximum pronation angles. Differences were significant for the flat shoe (mean = .23
seconds) compared to the high narrow-heeled shoe (mean = .3 seconds) and the flat shoe compared to the high broad-heeled shoe (mean = .28 seconds), but not for the high narrow-heeled (mean = .3 seconds) shoe compared to the high broad-heeled shoe (mean = .28 seconds, overall $F = 4.3$ and overall $p = .0185$). There was a significant difference between the means of the flat shoe (mean = .23 seconds) and the high narrow heel (mean = .3 seconds, $F = 7.6$ and $p = .0079$). There was no significant difference between the means of the flat shoe (mean = .23 seconds) and the broad high heel (mean = .28 seconds) ($F = 4.5$ and $p = .0375$). But, it could be considered a trend. Therefore, it was decided to accept subhypothesis 1d. Subhypothesis 2d states: *There will be a difference between time to maximum pronation angles in high narrow heels and high broad heels*. There was no significant difference between the high narrow heel (mean = .3 seconds) and the high broad heel (mean = .28 seconds, $F = 0.39$ and $p = .5331$). Therefore, subhypothesis 2d was rejected.

Table 4.4: Summary of Time to Maximum Pronation Angles in Seconds

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All subjects</strong></td>
<td>.23 (.11)*</td>
<td>.30 (.13)*</td>
<td>.28 (.10)*</td>
<td>4.3</td>
<td>.0185</td>
</tr>
<tr>
<td>Differences (1,2)</td>
<td>vs. narrow</td>
<td></td>
<td></td>
<td>7.6</td>
<td>.0079</td>
</tr>
<tr>
<td>Differences (2,3)</td>
<td>vs. broad</td>
<td></td>
<td></td>
<td>0.39</td>
<td>.5331</td>
</tr>
<tr>
<td>Differences (1,3)</td>
<td>vs. flat</td>
<td></td>
<td></td>
<td>4.5</td>
<td>.0375</td>
</tr>
</tbody>
</table>

*= standard deviation
Time to Minimum Pronation Angles

Subhypothesis 1e states: *There will be a difference between time to minimum pronation angles in high heels and flat shoes.* The time it took to reach minimum rearfoot angles was significant for all 28 women (see Table 4.5). Differences were significant for the flat shoe (mean = -0.04 seconds) compared to the high narrow-heeled shoe (mean = .03 seconds) and the flat shoe (mean = -0.04 seconds) compared to the high broad-heeled shoe (mean = -0.01 seconds), as well as the high narrow-heeled shoe (mean = .03 seconds) compared to the high broad-heeled shoe (mean = -0.01 seconds, overall $F = 23.1$ and overall $p < .0001$). For the flat shoe (mean = -0.04 seconds) and the high narrow heel (mean = .03 seconds) there was a significant difference ($F = 44.4$ and $p = .0001$). The difference between the means of the flat shoe (mean = -0.04 seconds) and the high broad heel (mean = -0.01 seconds, $F = 7.7$ and $p = .0077$) was also significant. Subhypothesis 2e states: *There will be a difference between time to minimum pronation angles in high narrow heels and high broad heels.* Indeed, the means for the high narrow heel (mean = .03 seconds) the high broad heel (mean = -0.01 seconds, $F = 15.1$ and $p = .0003$) were significant. Both subhypotheses were accepted.
Table 4.5: Summary of Time to Minimum Pronation Angles in Seconds

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects</td>
<td>-.04 (.05)*</td>
<td>.03 (.06)*</td>
<td>-.01 (.03)*</td>
<td>23.1</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Differences (1,2)</td>
<td>vs. narrow</td>
<td></td>
<td></td>
<td>44.4</td>
<td>.0001</td>
</tr>
<tr>
<td>Differences (2,3)</td>
<td></td>
<td>vs. broad</td>
<td></td>
<td>15.1</td>
<td>.0003</td>
</tr>
<tr>
<td>Differences (1,3)</td>
<td></td>
<td></td>
<td>vs. flat</td>
<td>7.7</td>
<td>.0077</td>
</tr>
</tbody>
</table>

*= standard deviation

Stance Time

Subhypothesis 1f states: There will be a difference between stance times in high heels and flat shoes. Table 4.6 summarizes the results for stance time in seconds. The differences between the means of the stance times of all 28 women were not significant. Differences were significant for the high narrow-heeled shoe (mean = .72 seconds) compared to the high broad-heeled shoe (mean = .69 seconds), but not for the flat shoe (mean = .70 seconds) compared to the high narrow-heeled shoe (mean = .72 seconds) or for the flat shoe (mean = .70 seconds) compared to the high broad-heeled shoe (mean = .69 seconds, overall F = 5.3 and overall p = .0080). There was no significant difference between the means of the flat shoe (mean = .70 seconds) and the high broad heel (mean = .69 seconds), F = 0.65 and p = .4249) or the flat shoe (mean = .70 seconds) and the high narrow heel (mean = .72 seconds, F = 5.4 and p = .0237). Subhypothesis 1f was rejected.

Subhypothesis 2f states: There will be a difference between stance times in high narrow heels and high broad heels. There was a significant difference between the means of the narrow high heel (mean = .72 seconds) and the broad high heel (mean = .69 seconds, F = 9.8 and p = .0028). Therefore, subhypothesis 2f was accepted.
Table 4.6: Summary of Stance Time in Seconds

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects</td>
<td>.70 (.06)*</td>
<td>.72 (.05)*</td>
<td>.69 (.05)*</td>
<td>5.3</td>
<td>.0080</td>
</tr>
<tr>
<td>Differences (1,2)</td>
<td>vs. narrow</td>
<td></td>
<td></td>
<td>5.4</td>
<td>.0237</td>
</tr>
<tr>
<td>Differences (2,3)</td>
<td></td>
<td>vs. broad</td>
<td></td>
<td>9.8</td>
<td>.0028</td>
</tr>
<tr>
<td>Differences (1,3)</td>
<td></td>
<td></td>
<td>vs. flat</td>
<td>0.65</td>
<td>.4249</td>
</tr>
</tbody>
</table>

* = standard deviation

Range of Pronation

To calculate the range of rearfoot motion, the minimum angles can be deducted from the maximum angles. Since two values for the minimum were determined — the true minimum and the rearfoot angle at heel strike — both ranges were calculated. The difference between the means for the range of motion using the maximum pronation minus the minimum pronation values was not significant. The range of motion using the maximum pronation minus the pronation angle at heel strike was significant.

Range of Pronation (Maximum minus Minimum Values)

Subhypothesis 1g states: "There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the minimum pronation angle." As shown in Table 4.7, the differences between the means of the range of rearfoot angles in degrees using the maximum rearfoot angles minus the
minimum rearfoot angles were not significantly different (overall $F = 2.0$ and overall $p = .1453$). There was no significant difference between the means of the flat shoe (mean = 8.0 degrees) and the high narrow heel (mean = 8.1 degrees, $F = 0.001$ and $p = .9819$) and the flat shoe (mean = 8.0 degrees) and the high broad heel (mean = 7.2 degrees, $F = 3.0$ and $p = .0911$). Subhypothesis 1g was rejected. Subhypothesis 2g states: *There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the minimum pronation angle.* There was no significant difference between the means of the narrow high heel (mean = 8.1 degrees) and the broad high heel (mean = 7.2 degrees, $F = 3.0$ and $p = .0870$). Subhypothesis 2g was also rejected.

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>$F$</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All subjects</strong></td>
<td>8.0 (2.2)*</td>
<td>8.1 (3.1)*</td>
<td>7.2 (2.8)*</td>
<td>2.0</td>
<td>.1453</td>
</tr>
<tr>
<td>Differences (1,2)</td>
<td>vs. narrow</td>
<td></td>
<td></td>
<td>0.001</td>
<td>.9819</td>
</tr>
<tr>
<td>Differences (2,3)</td>
<td></td>
<td>vs. broad</td>
<td></td>
<td>3.0</td>
<td>.0870</td>
</tr>
<tr>
<td>Differences (1,3)</td>
<td></td>
<td></td>
<td>vs. flat</td>
<td>3.0</td>
<td>.0911</td>
</tr>
</tbody>
</table>

* = standard deviation

**Range of Pronation (Maximum Pronation Angle Minus Pronation Angle at Heel Strike)**

Subhypothesis 1h states: *There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the pronation angle at heel strike.* The differences between the means of the range of rearfoot motion
angles using the maximum rearfoot angles minus the rearfoot angles at heel strike (see Table 4.8) were significantly different for the flat shoe (mean = 4.0 degrees) compared to the high narrow-heeled shoe (mean = 6.7 degrees) and the flat shoe (mean = 4.0 degrees) compared to the high broad-heeled shoe (mean = 5.9 degrees), but not for the high narrow-heeled shoe (mean = 6.7 degrees) compared to the high broad-heeled shoe (mean = 5.9 degrees, overall F = 11.2 and overall p < .0001). There was a significant difference between the means of the flat shoe (mean = 4.0 degrees) and the high narrow heel (mean = 6.7 degrees, F = 21.2 and p = .0001). There was also a significant difference between the means of the flat shoe (mean = 4.0 degrees) and the high broad heel (mean = 5.9 degrees, F = 10.3 and p = .0022). Subhypothesis 1g was accepted. Subhypothesis 2h states: There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the pronation angle at heel strike. There was no significant difference between the means of the narrow high heel (mean = 6.7 degrees) and the broad high heel (mean = 5.9 degrees, F = 2.0 and p = .1675). This parameter shows that there is a significant difference between flats and high heels, but not between two high heels of the same height with different heel dimensions. Therefore, subhypothesis 2h was rejected.
Table 4.8: Summary of the Range of Rearfoot Angles (Max-Angles at HS) in Degrees

<table>
<thead>
<tr>
<th></th>
<th>flat shoes</th>
<th>high narrow heels</th>
<th>high broad heels</th>
<th>F</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>All subjects</td>
<td>4.0 (2.4)*</td>
<td>6.7 (3.3)*</td>
<td>5.9 (2.4)*</td>
<td>11.2</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Differences (1,2)</td>
<td>vs. narrow</td>
<td></td>
<td></td>
<td>21.2</td>
<td>.0001</td>
</tr>
<tr>
<td>Differences (2,3)</td>
<td>vs. broad</td>
<td></td>
<td></td>
<td>2.0</td>
<td>.1675</td>
</tr>
<tr>
<td>Differences (1,3)</td>
<td>vs. flat</td>
<td></td>
<td></td>
<td>10.3</td>
<td>.0022</td>
</tr>
</tbody>
</table>

* = standard deviation

Summary

Rearfoot angles are one of the variables of interest in assessing the comfort aspects and stability of women’s high-heeled shoes. The purpose of this study was to compare rearfoot stability in the performance of women’s high-heeled shoes with different heel dimensions. To do this, the relationship between heel height, shoe-to-ground contact area and rearfoot angular stability in three different shoe styles: a flat shoe, a high narrow-heeled shoe, and a high broad-heeled shoe was investigated. It was expected that rearfoot range of motion would be greater in high heels than in flat shoes. This expectation was confirmed. It was also expected that the maximum pronation angles would be greatest for the high narrow-heeled shoe and least for the flat shoe with the high broad-heeled shoe falling in-between. Contrary to this expectation, the flat shoe showed the largest maximum pronation angles. The high narrow-heeled shoe, which was expected to have the largest rearfoot angles or be the least stable, had an overall smaller mean for maximum rearfoot pronation than the flat shoe, but their means were not significantly different. The high broad-heeled shoe showed the smallest maximum pronation angles.
When range of rearfoot motion (maximum pronation minus pronation at heel strike) was used as an indicator for rearfoot stability, the results confirmed the expectation that there would be a difference between the flat shoes and the high heels and a difference between the two high heels with different heel dimensions. Both the flat shoe and the high narrow heel showed an average maximum rearfoot angle of about twelve (12) degrees, whereas the high broad heel only showed an average maximum rearfoot angle of about nine (9) degrees. Range of rearfoot motion (maximum pronation minus pronation at heel strike) was a better indicator of rearfoot stability than maximum pronation.

The findings of the present study suggest that range of rearfoot motion is not only influenced by the height of the heel in a high-heeled shoe but may also be affected by its shape. An increase in surface area of the heel by 1/10 inches² [311 mm²] from a total area of 1/20 inches² [63 mm²] to 1/8 inches² [374 mm²], or an increase of nearly 600% (594%) resulted in a significant decrease in the measured maximum rearfoot angles and the rearfoot angles measured at heel strike. By comparison the heel area of the flat shoe was 7/8 inches² [2160 mm²] or about 3500% of the high narrow-heeled shoe. By contrast, maximum pronation, the value generally used to characterize rearfoot stability is not influenced by the same factors.
CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this study was to examine rearfoot stability in the performance of women’s high-heeled shoes with different heel dimensions. Three shoe styles were compared: flat shoes, high narrow heels, and high broad heels (both high narrow and high broad heels were 2 1/2 inches [6.4 cm] in height. Three-dimensional kinematic data analysis using the Qualisys® MacReflex System was used to calculate the rearfoot angles for each subject for five consecutive left foot strides. The measured variables included Maximum Pronation, Minimum Pronation, Pronation at Heel Strike, Time to Maximum Pronation, Time to Minimum Pronation, Stance Time, and Range of Pronation using both the Maximum Pronation minus the Minimum Pronation as well as the Maximum Pronation minus the Pronation at Heel Strike.

Objectives of the Study

In order to achieve the purpose of this study, the following objectives were formulated:

1. To develop a procedure to compare the kinematic observations of rearfoot stability while walking on a treadmill in two high-heeled shoes with different heel types to that of walking in a flat shoe (this constitutes a total of three pairs of shoe styles) between subjects.

2. To compare the results of rearfoot angle measurements with the answers from the questionnaire for the three different types of shoe styles (two high heels and one flat).
Hypotheses

**Hypothesis 1**: There will be a difference between rearfoot stability in high heels and flat shoes.

a. There will be a difference between the maximum pronation angles in high heels and flat shoes. *This hypothesis was rejected because there was no difference between the flat shoe and the high narrow heel.*

b. There will be a difference between the minimum pronation angles in high heels and flat shoes. *This hypothesis was rejected because there was no difference between the flat shoe and the high narrow heel.*

c. There will be a difference between the pronation angles at heel strike in high heels and flat shoes. *

*This hypothesis was accepted.*

d. There will be a difference between time to maximum pronation angles in high heels and flat shoes. *This hypothesis was accepted, although the evidence for it might just indicate a trend.*

e. There will be a difference between time to minimum pronation angles in high heels and flat shoes. *This hypothesis was accepted.*
f. There will be a difference between stance time in high heels and flat shoes.
   This hypothesis was rejected because there was only a trend apparent for the flat shoe and the high narrow heel and there was no difference between the flat shoe and the high broad heel.

g. There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the minimum pronation angle.
   This hypothesis was rejected because there was no difference between the flat shoe and the high narrow heel or the flat shoe and the high broad heel.

h. There will be a difference between the ranges of rearfoot motion in high heels and flat shoes using the maximum pronation angle minus the pronation angle at heel strike.
   This hypothesis was accepted.

**Hypothesis 2:** There will be a difference between rearfoot stability in high narrow heels and high broad heels.

a. There will be a difference between maximum pronation angles in high narrow heels and high broad heels.
   This hypothesis was accepted.

b. There will be a difference between minimum pronation angles in high narrow heels and high broad heels.
   This hypothesis was accepted.

c. There will be a difference between pronation angles at heel strike in high narrow heels and high broad heels.
   This hypothesis was accepted.
d. There will be a difference between time to maximum pronation angles in high narrow heels and high broad heels.

*This hypothesis was rejected because there was no difference between the high narrow heel and the high broad heel.*

e. There will be a difference between time to minimum pronation angles in high narrow heels and high broad heels.

*This hypothesis was accepted.*

f. There will be a difference between stance times in high narrow heels and high broad heels.

*This hypothesis was accepted.*

g. There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the minimum pronation angle.

*This hypothesis was rejected because there was no difference between the high narrow heel and the high broad heel.*

h. There will be a difference between the ranges of rearfoot motion in high narrow heels and high broad heels using the maximum pronation angle minus the pronation angle at heel strike.

*This hypothesis was rejected because there was no difference between the high narrow heel and the high broad heel.*

Findings

The following are the major results of this study:

1. There was a significant difference between the three shoe styles using the range of rearfoot motion (maximum pronation minus the pronation at heel strike) with the
flat shoe showing the least, the high narrow-heeled shoe showing the most, and the high broad-heeled shoe showing less than the high narrow heel but not as little as the flat shoe.

2. There was a significant difference in maximum and minimum pronation angles between the high narrow-heeled shoe and the high broad-heeled shoe. There was no significant difference in maximum and minimum pronation angles between the high narrow-heeled shoe and the flat shoe.

3. There were no significant differences between temporal aspects with regard to rearfoot stability in the three shoe styles investigated.

4. Subjects tended to wear a whole shoe size larger in fashion shoes (narrow toe box) than their measurements with a Brannock® device suggested. There was no difference between the means of the sizes for the three shoe styles each subject wore during the study (most subjects wore the same size for all three styles).

5. Older subjects tended to own more high-heeled shoes and wear them more often and longer than younger subjects. This may be due to current consumer trends.

Conclusions

Although comfort in high-heeled shoes has not been investigated extensively in the scientific community, it has received much attention in the popular press. At the outset of this study, rearfoot stability had not been researched in high-heeled shoes at all, and there are only three studies dealing with this subject which have been published since this study was undertaken. Of these, none has compared the influence of different heel shapes on rearfoot angles.
The purpose of this study was to examine rearfoot stability in the performance of women’s high-heeled shoes with different heel dimensions. Results from the questionnaire and the clinical assessment were used to complement the kinematic data. The biomechanical variables studied were rearfoot angles (maximum, minimum, and pronation at heel strike), temporal aspects (time to maximum, time to minimum, and stance time), and range of motion (maximum minus minimum and maximum minus pronation at heel strike). The questionnaire items of interest were anthropometric measures (age, height, weight, foot, and hand dominance), shoe size (measured, worn, self-reported, and width), and numbers of shoes owned and worn by subjects. Successfully completing all elements of this study fulfilled objective 1: To develop a procedure to compare the kinematic observations of rearfoot stability while walking on a treadmill in two high-heeled shoes with different heel types to that of walking in a flat shoe (this constitutes a total of three pairs of shoe styles) between subjects.

The results of this study cannot be applied to the general population or to shoes other than those tested, yet the analysis revealed a significant difference between rearfoot angles of the flat shoe and the high narrow-heeled shoe compared to the high broad-heeled shoe. Results showed that maximum pronation was similar in the flat and high narrow-heeled shoe. For the temporal aspects, the results showed mainly trends, not significant findings. The only exception was the time to minimum pronation which showed significant differences between all three shoe styles. No significant difference between the range of rearfoot motion for the value for maximum rearfoot motion minus minimum rearfoot motion was found whereas a significant difference between the means for all respective heel heights was found when the value for maximum rearfoot motion minus the rearfoot angle at heel strike was used.

The questionnaire and the clinical assessments did not reveal any unusual parameters that had a significant impact on the way in which the biomechanical findings should be
interpreted. None of the questionnaire variables chosen for further analysis showed a strong correlation with the kinematic variables. Comparing the questionnaire to the kinematic data fulfilled objective 2: *To compare the results of rearfoot angle measurements and the answers from the questionnaire for the three different types of shoe styles (two high heels and one flat).* There were some trends with regard to the temporal aspects of rearfoot stability related to age. The significant differences between age groups reported in previous studies about lumbar lordosis and knee flexion in high-heeled shoes (Opila-Correia, 1990) could not be repeated in this study. It seems logical that women who are older have had more time to accumulate shoes and that recent changes in fashions have led younger women who are just building their shoe wardrobes to wear lower and broader heels than older women. It is interesting that the women participating in this study wore an entire shoe size larger in classically-styled pumps than they measured. The most important finding was that range of rearfoot motion is the best measurement to use as an indicator for rearfoot stability.

During the planning stages of this study, no rearfoot angle findings were available for high-heeled shoes. Only Adrian and Karpovich (1966) had mentioned that rearfoot angles decrease in high-heeled shoes (3.375 inches [8.6 cm]). Since then, three studies have been published which investigate this aspect of high-heeled gait (Ebbeling et al., 1994; Hontalas and Williams, 1995; Snow and Williams, 1994). Ebbeling et al. investigated four different heel heights (0.5 inches [1.25 cm], 1.5 inches [3.81 cm], 2 inches [5.08 cm], and 3 inches [7.62 cm]) and found that rearfoot pronation was greatest in the 2 inch heel and least in the 3 inch heel with the 1/2 inch and 1 1/2 inch heel pronation values falling in between but closer to the values for the 3 inch heel. The angles were in order (from low to high heel height) 9, 8, 12, and 6 degrees on average for the respective heel heights. In Snow and Williams (1994), rearfoot angles in three different shoe styles (0.75 inches [1.91 cm], 1.5 inches [3.81 cm], and 3 inches [7.62 cm]) were smallest for the highest heel as well, with
the angles for the two lower heels falling inversely above them. The angles were in order (from low to high heel height) about 8, 6 and 5 degrees for the respective heel heights. Hontalas and Williams (1995) also showed a decrease in rearfoot angle in high high-heeled shoes (3 inches [7.62 cm]) as compared to medium-heeled shoes (1.5 inches [3.81 cm]) by about three (3) degrees, although this change was not significant. The angles were in ascending order about 14 and 11 degrees for the respective heel heights. It has to be noted that the two-dimensional versus three-dimensional values reported in Hontalas and Williams’ study (1995) were not consistent and only the three-dimensional values are being used for comparison in this study. The results from the studies of Ebbeling et al., Hontalas and Williams, and Snow and Williams (1994, 1995, 1994) corroborate the findings of this study that maximum pronation decreases with an increase in heel height. Although these researchers did not investigate differently-sized heels or did not identify the heel dimensions of the shoes used in their studies, comparing all four studies leads one to believe that there seems to be a critical value between two and three inches in heel height where maximum pronation decreases significantly when compared to lower heels or flat shoes.

Opila-Correia (1990) investigated stance phase time and found a significant increase for high-heeled (2.4 inches [6.1 cm]) compared to low-heeled (0.6 inches [1.6 cm]) shoes. This cannot be substantiated in this study. De Lateur et al. did not find significant differences between high heels (3.5 inches [8.9 cm]) and low heels (0.9 inches [2.2 cm]) with respect to stance time either. Neither Ebbeling et al. (1994), Hontalas and Williams (1995), nor Snow and Williams (1994) reported stance time in their published papers. Only Ebbeling et al. (1994) reported the time to maximum rearfoot angle as a percentage of stance time. The times were in order (from low to high heel height) 47%, 56%, 59%, and 62%. This compares to 33% (flat shoe), 42% (high narrow heel), and 41% (high broad heel) in this study. The large difference between the two groups may be attributable to the
age and experience of the subject groups. Ebbeling et al. (1994) investigated 15 subjects with a mean age of 23.3 (SD = 2.9) of which only seven were considered ‘experienced’ high-heel wearers. This study used 28 subjects with a mean age of 37.5 (SD = 9.5), all of whom were considered ‘experienced’ high-heel wearers. When this group was split into younger and older subjects, the values for the younger group with a mean age of 29.4 (SD = 4.1) could be more closely compared to those of Ebbeling et al. For the younger group, times to maximum pronation were in order (from low to high heel height) 33%, 51%, and 44% and 37%, 44%, and 41% for the older group. This shows that older and more experienced subjects show a more consistent pattern for temporal aspects than younger subjects.

Neither Ebbeling et al. (1994) nor Snow and Williams (1994) reported the difference between the ranges of rearfoot motion for the different heel heights. In this study, there was no significant difference between the range of rearfoot motion if the value for maximum pronation minus minimum pronation was used. There was a significant difference between the means for the respective heel heights when the value for maximum pronation minus pronation angle at heel strike was used. This difference may support the choice of using the true minimum rearfoot angle in addition to the pronation angle at heel strike as the minimum value, despite the fact that the minimum rearfoot angle lies on average several fractions of a second before heel strike for the flat shoe, very near heel strike for the high broad-heeled shoe, and a few fractions of a second after heel strike for the high narrow-heeled shoe.

Implications and Recommendations

The comparison of recent studies on rearfoot stability in women’s high-heeled shoes to the results of this study suggests that wearing high heels hampers the natural pronation
which unlocks the foot for surface adaptation that takes place in walking. In this study, there was no significant difference between the high narrow heel and the flat shoe with regard to maximum pronation but the high broad heel compared to both the high narrow heel and the flat shoe showed a significant decrease in maximum pronation. This might mean that if the heel dimension of a high-heeled shoe is increased, the material the heel is made from may have to be a softer material to compensate for the loss of cushioning. Otherwise, the prolonged wearing of high-heeled shoes may lead to injuries in the knees or hips in the long term. It might also mean that the rearfoot range of motion is a better indicator for rearfoot stability and should be preferred over maximum pronation.

Developing more sophisticated questionnaires and integrating them with clinical assessment values as well as rearfoot angle data may yield a tool to allow a more detailed assessment of comfort in high-heeled shoes. As several previous studies, for example Opila-Correia (1988, 1990a, b), Snow and Williams (1992, 1994), Ebbeling et al. (1994), and Hontalas and Williams (1995) showed, high-heeled shoes have an effect on parts of the body besides the rear of the foot. Therefore, future studies might evaluate other biomechanical parameters in addition to rearfoot stability.

To gain further insight into an ‘ideal’ range of heel heights and shapes, future studies on rearfoot stability in high-heeled shoes might investigate additional heel dimensions (height, width, and shape) to see if there is a linear, an exponential, or an inverse relationship between the rearfoot angle values resulting from different heel dimensions and if there is a critical heel height at which the average rearfoot pronation in high-heeled shoes changes. If future researchers had access to shoe prototype manufacturing facilities, experimentation with heel materials of different densities may add an interesting dimension to the study of rearfoot stability in high-heeled shoes.
BIBLIOGRAPHY


APPENDICES
Appendix A: Candidate Screening Questionnaire

Dear high heel wearer:

I would very much appreciate your help with my master’s thesis. If you would like to participate in a Shoe Research Study at Oregon State University, please take a moment to fill in the following questions. I would require about one-half to one hour of your time on two different days between March 22 and April 30, 1995. The study will involve walking on a treadmill in high-heeled shoes (provided by me) and filling out a questionnaire about shoe preferences.

If you are interested in helping with this study, please respond to the following questions. If your response to question 1 is “no,” you may want to pass this card to a friend who you think could answer “yes.” Thank you very much.

**Do you wear high heels regularly (2 or 3 days a week for at least 8 hours per day)?**

- [ ] Yes
- [ ] No

**Is your shoe size between 6 and 9?**

- [ ] Yes
- [ ] No

**Is your age between 20 and 54?**

- [ ] Yes
- [ ] No

**Is your height between 5' and 5'10'?**

- [ ] Yes
- [ ] No

**Have you had any injuries to your leg, ankle, or foot in the past five years?**

- [ ] Yes
- [ ] No

If yes, what type of injury?

**If you are willing to participate in this study,**

**What is your name?**

______

and,

**What is your phone number?**

______

I will call you in the next few days to find out a few more details about you (I am looking for participants with particular characteristics) and tell you a little more about the study. If you fit the participant profile, I will schedule the two meeting times with you. If you have any questions now before you fill out these questions, feel free to contact me.

- My name is: Dörte Engel
- My number is: 758-0917 (I work days, so please call evenings or weekends)
- My e-mail address is: dorte@terrapacific.com

Thank you very much for supporting research at Oregon State University.
Appendix B: Consent Form

CONSENT FORM

TITLE: Biomechanical study of the rearfoot stability of women's high-heeled shoes

INVESTIGATORS: DÖRTE ENGEL, B. S., NANCY BRYANT, M. A., GERALD SMITH, PH.D.

PURPOSE: This study will determine if the relationship between the height of a shoe and its ground-contact area have an effect on a person's rearfoot stability.

I have received an oral explanation of the study procedures and understand that they entail the following:

All testing will be conducted in the Biomechanics Laboratory in the Women's Building at Oregon State University. As a subject, I will report to the laboratories on time for the following procedures:

1. I will undergo a brief physical foot examination to determine my overall foot health.

2. I will complete a questionnaire.

3. I will practice walking on the treadmill to familiarize myself with the data collection procedure.

4. For the data collection, I will be asked to walk on a treadmill in three shoe types while being video taped.

The first data collection session will take at least one half hour but should not exceed one hour in length. The second session will take at least fifteen minutes but should not exceed one half hour in length. I understand that the risks or discomfort resulting from my participation may include muscle soreness, elevated heart rate, elevated breathing rate, and increased sweating. The risk of falling off the treadmill while walking in high-heeled shoes is small but does exist. Since walking on the treadmill in high-heeled shoes may be difficult at first, I will be given adequate time to practice and become comfortable with the procedure. I should be aware that if I sustain injuries in the process of testing, the University and the researchers will not be held responsible.
As a direct benefit of this study, the researcher will send me a brief summary of its outcome and a written recommendation for choosing well-fitting dress shoes. Results of this study will be submitted for publication using only cumulative results from all subjects. Strict anonymity about any personal parameters collected during this study will be maintained. Video tape images will only include the lower portion of the legs, so subjects will not be able to be identified. After the research is completed, the video tapes will be erased.

I understand the nature and purpose of this research. The researchers have offered to answer any further questions I may have. I should be aware that Oregon State University does not provide research subjects with compensation or medical treatment in the event the subject is injured. It is not expected that any injury or harm should occur to me as a result of participating in this study, but I should be aware of this University rule. My participation is completely voluntary and I may decide to withdraw from the study at any time.

Questions about the research and my rights should be directed to:

DÖRTE ENGEL, Graduate Student or NANCY BRYANT, Associate Professor, Oregon State University, Milam Hall 224, Corvallis, Oregon 97331, Telephone: (503) 737-0989

I have read the above information and agree to participate in this study.

_____________________________  ______________________________
(signature of investigator)      (today's date)

_____________________________
(my address)

I certify, that I have explained the nature and purpose, the potential benefits and possible risks associated with participation in this research study to the above signed individual. I have answered any questions that have been raised and have witnessed the above signature.

_____________________________  ______________________________
(signature of investigator)      (today's date)
Appendix C: Subject Questionnaire

QUESTIONNAIRE ON WOMEN'S HIGH-HEELED SHOES:

This study will investigate the relationship between heel height, heel contact area with the ground and heel stability. Two video cameras will be used to record data. In order to make the video data more meaningful, you are asked to answer the following questions. All of the information collected will be used only for this study of feet and shoes. Confidentiality will be strictly maintained. "High heels" are shoes displaying a difference between the sole and the heel of the foot of one inch or more. In "flat shoes" the heel is no more than one half inch in height (if you are unsure how these shoes look, ask the researcher to show you sample pairs of each style).

DÖRTE ENGEL, GRADUATE STUDENT
OREGON STATE UNIVERSITY
MILAM HALL 224
CORVALLIS, OREGON, 97331
758-0917 OR 737-0989
E-MAIL: DORTE@TERRAPACIFIC.COM
**QUESTIONNAIRE ON WOMEN’S HIGH-HEELED SHOES:**

1. Please give your shoe size or length (*Use inches [e. g. 7 1/2] or centimeters [e. g. 38], whichever you prefer*) and width (*Indicate with a letter: A, B,..., EEE*):

<table>
<thead>
<tr>
<th></th>
<th>American:</th>
<th>European:</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SIZE OR LENGTH</td>
<td>_____in</td>
</tr>
<tr>
<td>2</td>
<td>WIDTH</td>
<td>_____</td>
</tr>
</tbody>
</table>

2. At what age did you first wear high heeled shoes 1" or higher in height? (*Please circle one number at left*)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>BEFORE AGE 15</td>
</tr>
<tr>
<td>2</td>
<td>15 - 20</td>
</tr>
<tr>
<td>3</td>
<td>20 - 25</td>
</tr>
<tr>
<td>4</td>
<td>25 - 30</td>
</tr>
<tr>
<td>5</td>
<td>AFTER AGE 30</td>
</tr>
<tr>
<td>6</td>
<td>NEVER</td>
</tr>
</tbody>
</table>

3. Approximately how many pairs of the following shoe types if any, do you own (as best as you can recall)?

<table>
<thead>
<tr>
<th></th>
<th>NUMBER</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Broad high-heeled shoes (2&quot; or higher)</td>
<td></td>
</tr>
<tr>
<td>b. Narrow high-heeled shoes (2&quot; or higher)</td>
<td></td>
</tr>
<tr>
<td>c. High heeled sandals (2&quot; or higher)</td>
<td></td>
</tr>
<tr>
<td>d. Medium-heeled pumps and/or sandals (1&quot;-2&quot;)</td>
<td></td>
</tr>
<tr>
<td>e. Cowboy boots (with 1&quot;-2&quot; heels)</td>
<td></td>
</tr>
<tr>
<td>f. Flat dress shoes</td>
<td></td>
</tr>
<tr>
<td>g. Flat sandals</td>
<td></td>
</tr>
<tr>
<td>h. Casual slip-on shoes</td>
<td></td>
</tr>
<tr>
<td>i. Loafers/oxfords</td>
<td></td>
</tr>
<tr>
<td>j. Lace casual shoes</td>
<td></td>
</tr>
<tr>
<td>k. Winter boots with heels</td>
<td></td>
</tr>
<tr>
<td>l. Winter boots without heels</td>
<td></td>
</tr>
<tr>
<td>m. Work boots</td>
<td></td>
</tr>
<tr>
<td>n. Uniform shoes</td>
<td></td>
</tr>
<tr>
<td>o. Tennis/running/sports shoes</td>
<td></td>
</tr>
<tr>
<td>p. Ski boots/ice-skates/roller blades</td>
<td></td>
</tr>
</tbody>
</table>
4. Do you wear high heels more often than you did **five years ago**, less often, or with the same frequency? *(Please circle one number)*

1. **MORE OFTEN**
2. **LESS OFTEN**
3. **SAME FREQUENCY**

5. How often do you wear high heels 1" or higher? *(Please circle one number at left)*

1. **NEVER**
2. **ONLY ON SPECIAL OCCASIONS (LESS THAN ONCE A MONTH)**
3. **LESS THAN ONCE A WEEK (BUT AT LEAST ONCE A MONTH)**
4. **ONCE OR TWICE A WEEK**
5. **THREE OR FOUR TIMES A WEEK**
6. **FIVE TO SIX TIMES A WEEK**
7. **ALMOST DAILY**

6. When you wear heels, do you wear them the entire day, part of the day, or only until it is 'acceptable' to take them off? *(Please circle one number)*

1. **THE ENTIRE DAY**
2. **PART OF THE DAY**
3. **ONLY UNTIL 'SOCially ACCEPTABLE' TO TAKE OFF**

7. Please indicate how often you wear high heels to each of the following? *(Please circle one number for each)*

<table>
<thead>
<tr>
<th></th>
<th>OFTEN</th>
<th>SOMETIMES</th>
<th>RARELY</th>
<th>NEVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Formal occasions (e. g.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>weddings, parties)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Work</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>c. Interviews (job or other)</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>d. Work-related travel</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>e. Professional meetings</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>f. School</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>g. Church</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>h. Shopping</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>i. Movies</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>j. Dating</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>k. Dinner out</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>l. Driving</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
8. Please indicate whether or not the following shoe parts present fitting problems to you? If yes, please indicate whether they are usually too wide or too narrow?

<table>
<thead>
<tr>
<th></th>
<th>NO</th>
<th>YES</th>
<th>TOOWIDE</th>
<th>TOO NARROW</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Toe box (toe area)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>c. Ball of the foot</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>d. Heel area</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

If yes, are they:

8. a) If yes, are shoes too long or too short? *(Please circle one number)*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TOO LONG</td>
</tr>
<tr>
<td>2</td>
<td>TOO SHORT</td>
</tr>
</tbody>
</table>

9. Do you have problems fitting the length of your foot? *(Please circle one number)*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NO</td>
</tr>
<tr>
<td>2</td>
<td>YES</td>
</tr>
</tbody>
</table>

8. a) If yes, are shoes too long or too short? *(Please circle one number)*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TOO LONG</td>
</tr>
<tr>
<td>2</td>
<td>TOO SHORT</td>
</tr>
</tbody>
</table>

10. Do you have problems fitting the instep (area across the top of your shoe)? *(Please circle one number)*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NO</td>
</tr>
<tr>
<td>2</td>
<td>YES</td>
</tr>
</tbody>
</table>

9. a) If yes, is there too much or too little room? *(Please circle one number)*

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TOO MUCH</td>
</tr>
<tr>
<td>2</td>
<td>TOO LITTLE</td>
</tr>
</tbody>
</table>

11. Have you experienced any of the following problems within the past five years? *(Please circle yes or no)*

<table>
<thead>
<tr>
<th></th>
<th>YES, I HAVE</th>
<th>NO, I HAVE NOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>a.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>b.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>c.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>d.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>e.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>f.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>g.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>h.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>i.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>j.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>k.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>l.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>m.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>n.</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>o.</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
12. Are the following factors very important, somewhat important, not too important, or not at all important in influencing your purchase of high heels? (Circle one response for each)

<table>
<thead>
<tr>
<th>How important is it?</th>
<th>VERY</th>
<th>SOMEWHAT</th>
<th>NOT TOO</th>
<th>NOT AT ALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Attractive style</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>b. Good value</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>c. Good quality</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>d. Spur of the moment</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>e. Comfort</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>f. Low price</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>g. Need to replace old ones</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>h. Need shoes to go with a certain outfit</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>i. Need shoes for a special occasion</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>

13. a) Please indicate whether or not you purchase high-heeled shoes in the following types of stores. (Circle the appropriate number)

<table>
<thead>
<tr>
<th></th>
<th>YES</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Specialty shoe store</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>B. Department store</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>C. Boutique</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>D. Chain store</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>E. Mail-order catalog</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>F. Discount store</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>G. Factory outlet</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>H. Retail outlet (such as Nordstrom's rack)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>I. Second hand (Goodwill etc.)</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

13. b) From the list in question 12. a) fill in the letters corresponding to the types of stores in which you purchase high heels most often, second most often, and third most often. (Fill in the appropriate letters)

______ MOST OFTEN
______ SECOND MOST OFTEN
______ THIRD MOST OFTEN

14. How much do you usually pay for a pair of high-heeled shoes? (Circle the appropriate number)

1 UNDER $10.00
2 $10.00-29.99
3 $30.00-49.99
4 $50.00-74.99
5 $75.00 OR OVER
15. Are you left-handed or right-handed? (Please circle the correct number)
   1  LEFT-HANDED
   2  RIGHT-HANDED
   3  AMBIDEXTEROUS

16. If you were asked to hop on one leg, would it be the left or the right leg? (Please circle the appropriate number)
   1  THE LEFT LEG
   2  THE RIGHT LEG
   3  EITHER

17. How many miles do you walk or run per week? (Circle the appropriate number for an average week)
   1  UNDER 7 MILES
   2  7-14 MILES
   3  15-21 MILES
   4  22-35 MILES
   5  36 MILES OR MORE

18. In which age category are you? (Please circle the appropriate number)
   1  20-24 YEARS
   2  25-29 YEARS
   3  30-34 YEARS
   4  35-39 YEARS
   5  40-44 YEARS
   6  45-49 YEARS
   7  50-54 YEARS

19. What is your height?
   HEIGHT: ________ ft ________ in  or  ________ cm

20. Which category includes your weight? (Please circle the appropriate number)
   1  100-109 LB OR LESS
   2  110-119 LB
   3  120-129 LB
   4  130-139 LB
   5  140-149 LB
   6  150-159 LB
   7  160-169 LB
   8  170-179 LB
   9  180-190 LB OR MORE
21. Which income group best describes your total household income before taxes in 1994 (1993, if you do not know the number for 1994 yet)? (Please circle one number)

1. UNDER $4,999
2. $5,000-$9,999
3. $10,000-$14,999
4. $15,000-$24,999
5. $25,000-$24,999
6. $35,000-$49,999
7. $50,000-$74,999
8. $75,000-$99,999
9. $100,000 AND OVER

22. Do you have any additional comments you would like to make regarding high-heeled shoes? (Feel free to write as much as you like)

-- THANK YOU VERY MUCH FOR PARTICIPATING IN THIS STUDY --
Appendix D: Physical Assessment Work Sheet

Subject #: Name: Age:

A. History of any injuries (including injury type and time):

B. Foot dominance: ___ left ___ right ___ ambidextrous

C. Observation (note any gross deformities and abnormal gait patterns):

D. Palpation (note any gross deformities and pain in the bone and soft tissue):

E. Special Tests:
1. Ankle Tests:
   a. Anterior Drawer (0 degrees):
      solid end point ___ yes ___ no
      within normal limits ___ yes ___ no
   b. Anterior Drawer (20 degrees passive flexion):
      solid end point ___ yes ___ no
      within normal limits ___ yes ___ no
   c. Side-to-Side:
      solid end point ___ yes ___ no
      within normal limits ___ yes ___ no
   d. Talor Tilt:
      solid end point ___ yes ___ no
      within normal limits ___ yes ___ no
2. Foot Tests:
   a. Foot Type:
      ___ greek    ___ square    ___ egyptian
   b. Arch Type:
      ___ normal    ___ pes planus    ___ pes cavus
   c. Toes:
      ___ normal
      ___ hammer toe    location(s):
      ___ claw toe    location(s):
      ___ corns    location(s):
   d. Knee:
      Q-angle: ________ degrees

3. Shoe Size:
   a. Left Foot    length:____   width:____
   b. Right Foot   length:____   width:____

4. Additional Remarks:

******************************************************************************

   ___ accept    ___ reject
# Appendix E: Summary of Relevant Questionnaire Results

## Table E.1: Anthropometric Characteristics of the 28 Subjects studied

<table>
<thead>
<tr>
<th>Subject(#)</th>
<th>Age (years)</th>
<th>Height (inches)</th>
<th>Weight (pounds)</th>
<th>Hand Dominance</th>
<th>Foot Dominance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48</td>
<td>62</td>
<td>115</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>2</td>
<td>27</td>
<td>62</td>
<td>115</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>66</td>
<td>115</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>4</td>
<td>35</td>
<td>63</td>
<td>115</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>5</td>
<td>24</td>
<td>64</td>
<td>125</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>6</td>
<td>35</td>
<td>65</td>
<td>125</td>
<td>2 (R)</td>
<td>1 (L)</td>
</tr>
<tr>
<td>7</td>
<td>35</td>
<td>70.5</td>
<td>185</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>8</td>
<td>25</td>
<td>61.5</td>
<td>135</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>9</td>
<td>27</td>
<td>63</td>
<td>145</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>10</td>
<td>25</td>
<td>62</td>
<td>145</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>11</td>
<td>38</td>
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<td>2 (R)</td>
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<td>12</td>
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<td>65</td>
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<td>66</td>
<td>185</td>
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<td>2 (R)</td>
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<td>46</td>
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<td>185</td>
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<td>2 (R)</td>
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<td>21</td>
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<td>185</td>
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<td>1 (L)</td>
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<td>125</td>
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<td>2 (R)</td>
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<td>33</td>
<td>67.5</td>
<td>145</td>
<td>2 (R)</td>
<td>2 (R)</td>
</tr>
<tr>
<td>24</td>
<td>42</td>
<td>66</td>
<td>155</td>
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<td>3 (Amb)</td>
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<td>25</td>
<td>53</td>
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<td>125</td>
<td>2 (R)</td>
<td>2 (R)</td>
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<td>145</td>
<td>2 (R)</td>
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<td>2 (R)</td>
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<td>31</td>
<td>67</td>
<td>135</td>
<td>1 (L)</td>
<td>1 (L)</td>
</tr>
</tbody>
</table>

| Mean       | 37.54       | 64.58           | 146.43          |
| SD         | 9.49        | 2.65            | 25.32           |
Table E.2: Measured and worn shoe sizes of the 28 Subjects studied

<table>
<thead>
<tr>
<th>Subject (#)</th>
<th>Measured shoe size (left)</th>
<th>Measured shoe size (right)</th>
<th>Wom size for flat shoe (left)</th>
<th>Wom size for high narrow-heeled shoe (left)</th>
<th>Wom size for high broad-heeled shoe (left)</th>
<th>Measured shoe width (left foot, A=1, B=2,...)</th>
<th>Measured shoe width (right foot, A=1, B=2,...)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6.5</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>6.5</td>
<td>1</td>
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<tr>
<td>2</td>
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<td>6.5</td>
<td>6.5</td>
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<td>7</td>
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</tr>
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Table E.3: Number of pairs owned and frequency of wearing high-heeled shoes by the 28 subjects studied

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