A Biomechanical Evaluation of Standing in High- Heeled Shoes

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ABSTRACT

The purpose of this study was to determine the action of the ground reaction force upon the heels of women standing in high-heeled shoes. The study involved a non-invasive determination of the location of the subtalar joint axis, the joint about which the foot bends in and out. It was determined where the ground reaction force acts relative to the subtalar joint axis and whether muscle activity while standing depends on this result. Five healthy female volunteers will stand while wearing 2.5” heels, 1” heels, and barefoot while ground reaction forces and electrical muscle activity were recorded.

INTRODUCTION

Historical Perspective

Stilettos. Boots. Pumps. “Open toed.” Around the age of twelve, girls all over embarked on their first pair of high-heels. Historically, the first form of high heels as we know started during the 14th century. Gentry and noble men started placing wooden slips, called platens, to the bottom of their footwear to protect them from getting dirty. (Linder and Saltzman, 1998) However, in later days they have become a characteristic of femininity and an accepted custom for women in our society. Through the evolution of time, several features have made high heels distinguishable in comparison to other shoes worn by women. On the average, shoes have a heel elevation of approximately 1 to 2 cm; however, high-heeled shoes can have a heel height greater than 10 cm high. High-heeled shoes also pose a narrow toe box, a rigid heel cap that often protrudes anteriorly (Stephens, 1992) and excessive plantar curvature in the forefoot (Schwartz and Heath, 1959). Whether it is to gain a height advantage, look professional, or stay with the trend of fashion, it is not entirely uncommon for a woman to own a hundred pairs of these shoes at one time. Wearing such footwear can often have deleterious and irreversible biomechanical effects. (Linder and Saltzman, 1998) “For 250 years medical scientists have propagandized about the health hazard of high heeled shoes, …". (Linder and Saltzman, 1998)

Despite the uncomfortable feelings that some women experience while wearing high heeled shoes, heels are getting higher, inclines are steeper, and toe boxes are more pointed. (Lee et al., 2001) To achieve "toe cleavage" (toes that are perfectly aligned in pointed toed shoes), as it is known to the fashion-conscious world, more than half the members of the America Orthopedic Foot & Ankle Society are responding to women risking permanent disability of cosmetic foot surgery, such as shorten toes, at a cost of $2,300 per toe and collagen injection into the balls of the feet. The collagen serves to restore lost padding caused by frequent high heel usage and costs approximately $500 per injection. (Harris, 2003) While ample research is done on the biomechanics of high-heeled shoes, research has yet to look at the anatomical differences and biomechanics principles of the subtalar joint axis in relation to its' effect of standing in high heel shoes. The study will seek to answer the following questions:

1. How does the ground reaction force act upon the heels of women who wear heel-heeled shoes?
2. How does this action vary across subjects in accordance to the location of their subtalar joint axis?
3. How does muscle activity patterns correspond to the action of the ground reaction force?

Significance of the study

The data collected in this project is of relevance because the subjects- women are a large segment of the world's population. A census brief entitled "Women in the United States: A Profile", projected women to outnumber men by 10 million by the year 2005. (Spraggins, 2005) A 1986 Gallup Organization survey determined that 59% of the women surveyed associated wearing high heel shoes for at least one hour to more than eight hours a day. (The Gallup Organization Inc., 1986) This research can also help assist to educate women as to the effects of standing in high-heeled shoes and may positively influence the design of high-heeled shoes, which could lead towards a more comfortable and anatomically correct shoe. In addition, the study may clear up assumptions that all women should avoid wearing high-heeled shoes and formulate a link to the anatomical variations of women and effects of high-heeled shoes.

RELATED LITERATURE

Literature was reviewed in the following topic areas: subtalar joint axis, ground reaction forces, and muscular activity.

Subtalar Joint Axis

The subtalar joint (figure 1) is a composite joint formed by three separate plane articulations located superiorly to the talus and inferiorly to the calcaneus. Together, the three surfaces provide a triplanar movement around the single joint axis and one of the functional joints of the foot and ankle.

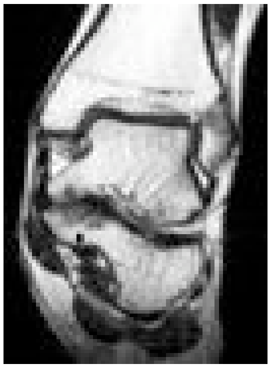


Figure 1. Subtalar joint axis

Often reported as a single axis, a helical screw axis and a bundle of axes, the subtalar joint is responsible for several movements about the ankle; inversion and eversion in the transverse plane; plantar flexion and dorsiflexion in the sagittal plane; and adduction and abduction in the frontal plane. “Subtalar inversion helps to bring about stability of the foot during single-limb stance.”(Backus and Sherry, 1999) Subtalar eversion occurs as a mechanism of shock absorption when the foot makes contact with a surface. Five muscles help control inversion of the subtalar joint axis and cross the medial side of the joint: tibialis posterior, tibialis anterior, flexor digitorum longus, flexor hallucis, and soleus. Four muscles are responsible for eversion of the subtalar joint axis: extensor digitorum longus, peroneus tertius, peroneus longus, and peroneus brevis (figure 2).

Figure 2. Muscles that cross the subtalar joint axis.

It is the motion at this joint that permits the foot to adapt to a variety of surfaces (Wright et al., 1964). “In addition there is substantial variability in the orientation of this axis in normal individuals; thus the relative motions will also vary among normal individuals.” (Backus and Sherry, 1999) The subtalar joint axis has a wide accepted range of deviation and inclination. The range of deviation is 4 degrees to 47 degrees with a standard deviation of 11 degrees and a mean deviation of 23 degrees. Subtalar inclination ranges from 20.5 degrees to 68.5 degrees with a standard deviation of 9 degrees and mean range being 42 degrees. (Isman and Inman, 1969)

Ground Reaction Forces

Ground reaction force (GRF) is any external reaction force, specifically one applied by the ground. Ground reaction force is equal in magnitude and opposite in direction to the force that the body exerts on the supporting surface through the foot. GRFs can be represented by Newton 3rd law of motion, action reaction pair.

Several studies have viewed and reported increased pressure under the forefoot with an increase in heel heights in women wearing high-heeled shoes. However few studies have measured GRFs. In a study done by Opila-Correla, K.A. (1990), no significant differences in GRFs were found between younger and older wearers or between experienced and inexperienced high heeled shoe wearers. Another study, measured vertical, anteroposterior and mediolateral direction of GRFs of a women's gait in three different heel heights. The study showed an increase in vertical, anteroposterior and mediolateral ground reaction forces with increased heel height. The highest heel height of 7.62 cm showed a pronounced inflection point compared to those of the lower heels and medium heels tested for vetrical GRFs. Anteroposterior and mediolateral GRF appeared later in the stance and support phases for the higher heel height, but did show a significant increase.

Muscular Activity

In high heel gait and standing, many muscles located in the lower extremities and the back are overly worked due to the plantar flexion of the foot. Muscles are at their peak for force generation when they are at resting length. When muscle length increases or decreases beyond its resting length, muscle force production decreases in a bell shaped form. This relationship is seen in high heel wearers. When the heel is raised, as in wearing high-heeled shoes, muscles fibers that innervate the muscles along the leg are shorten. The shortened muscles are now inconsistent with its resting length-tension relation resulting in less force production. Esenyel et al. (2001), found "… the exaggerated plantar flexed position of the ankle joint places the gastro-soleus muscle at a shortened and thus less favorable position on its muscle length-tension curve. Under such conditions, the plantar flexion musculature is in a less advantageous position for power and work generation and consequently less propulsive abilities. (Esenyel et al., 2001)

METHODOLOGY

Five female subjects between the ages of 18-24 years of age were recruited from the local Pennsylvania State University community for this study. Their age, height, weight and shoe size were recorded. The subjects reported not having any musculoskeletal or neuromuscular abnormalities that restrict the range of lower extremity motion, which might make the wearing of high-heeled shoes painful. All subjects were experienced wearers of high-heeled shoes as evidenced by self-reported wearing usage of at least twice per week. These criteria were established to control variation among subjects in their motor control that could result in differences in habitual versus sporadic high-heeled shoe wearers. All methods were in accordance with the guidelines set forth by the Human Subjects Review Board of The Pennsylvania State University, University Park, Pennsylvania.

Two different shoes (figure 3) were used in this investigation. The first shoe, a flat open toed shoe, had an average heel height of 1 cm and a stacked block heel. The second shoe was a high-heeled open toed shoe with an average heel height of 2.5 cm with a stiletto-spiked heel. Both shoes were commercially available and purchased through a Payless Shoe manufacturer. The shoes were primarily chosen due to their similarity of construction at the forefoot and their access to the calcaneus so that the main difference between shoe models was the height and type of heel. Shoe sizes ranged from 7, 7.5, 8, 8.5,to 9.

Figure 3 Shoes used in the study. Shoe to the left, the flat, measures with a 1” heel. Shoe on the right, the high heel, measures a heel height of 2.5”.

Kinetic data of ground reaction force as well as the point of application of that force was collected with a Kistler Instrument. Corporation force plate mounted flush to the floor. Kinematic data was collected simultaneously with the kinetic data using a Video-based motion analysis system. An Eagle system (Motion Analysis Corporation.) that consisted of six video cameras tracked the locations of spherical reflective markers in three dimensions. Electromyographical activity was collected using a telemetered EMG system (Noraxon Corporation.). Recording electrodes were connected to a battery powered transmitting unit worn on the subject’s belt.

Determination of the subtalar joint axis was the first procedure that the subject undertook. Participants were asked to sit at the edge of a table to perform a non-invasive technique for location of the subtalar joint. The applications of eight, 9-mm-diameter reflective markers, using double sided tape were applied to the skin overlying the anterolateral aspect of the tibia and the lateral aspect of the calcaneus of the right leg on each subject. Four markers each were applied to the anterolateral tibia and the lateral aspest of the calacaneus in an asymmetrically box fashion. This was done to help increase the tracking of the cameras. Quiet standing of three seconds was done to record the location of the reflective markers to serve as a template for later tracking the location of the subtalar joint axis. Palpitation of six anatomical landmarks: the right lateral malleolus, right medial malleolus, right lateral tibial condyle, right medial tibial condyle, right foot heel, and the right second metatarsal head were done.

An additional 9-mm-diameter reflective markers were placed on these locations.In addition, markers were placed to help computerize the structure of the shank and foot. Three reflective markers were placed on the ground to help digitize the plane coordinates of the foot. Subjects were asked to stand for three seconds of quiet standing while the cameras recorded the location of the 17 markers (14 markers on the body and three on the ground). Participants then had the additional markers from the right lateral malleolus, right medial malleolus, right lateral tibial condyle, right medial tibial condyle, right foot heel, right second metatarsal head removed and the three placed on the ground to leave the remaining eight markers placed on the shank and calcaneus.

Participants were affixed to a Marionette System (figure 4) on the table so that feet were dangling. The participant's thigh was stabilized with a velcro strap and the foot was put into dorsiflexion by pulling up on the Marionette System as the forefoot is hanging from a platform by a velcro strap. Alternately pulling on the strings tension to produce a slow full side-to-side rocking motion of the foot was done to provide full usage of the subtalar joint axis. The motions of the eight markers were tracked using the Eagle system (Motion Analysis Corporation.) video-based motion analysis system. Ten 30-second trails were recorded for each to ensure accuracy.

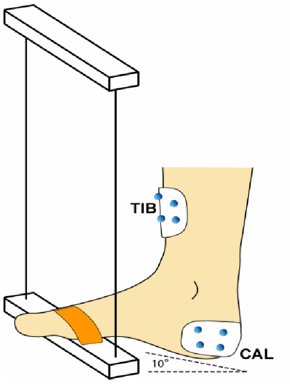


Figure 4. Non-invasive subtalar joint axis determination. The foot is moved about the subtalar axis and three-dimensional motion of the heel and shank is recorded.

Electromyographical activity of the tibialis anterior, peroneals, lateral gastrocnemius and medial gastrocnemius muscles were collected using surface electrodes. Skin preparation consisted of treating appropriate areas with alcohol swabs to ensure dead skin removal and increase EMG activity readings. Self-adhesive circular Ag/AgCl electrodes of 1-cm diameter were placed approximately 2 cm apart in the middle of the muscle bellies in an attempt to minimize cross talk and remain in the same placement for data collection of all shoes.

For each subject the order of the shoe condition was randomly assigned and three standing trails for five seconds each were collected for each condition. Subjects stood still in a normal relaxed position on a wooden platform two inches above the floor. (figure 5) A cutout in the platform contained a wooden block that rested atop the force place set in the floor in order to collect heel ground reaction force. The platform itself was supported by the floor and not the force plate. Subjects placed just the heel of the right shoe atop the wooden block.

Figure 5. Subject standing in high heels on platform over force plate

Lastly participants performed trails to elicit EMG percent maximal. Two trails for each muscle will be performed for five seconds each. For tibialis anterior subjects were asked to first walk on the outer foot borders for five seconds and then invert against manual resistance applied by the investigator. For the peroneal muscles, participants were asked to walk on the inner border of the foot for one trail and then evert against manual resistance applied by the investigator for the last trail. The participant was then asked to push against a wall using maximum force and then perform a resistant toe rise for trails to elicit percent maximum of EMG activity in the gastrocnemius muscle.

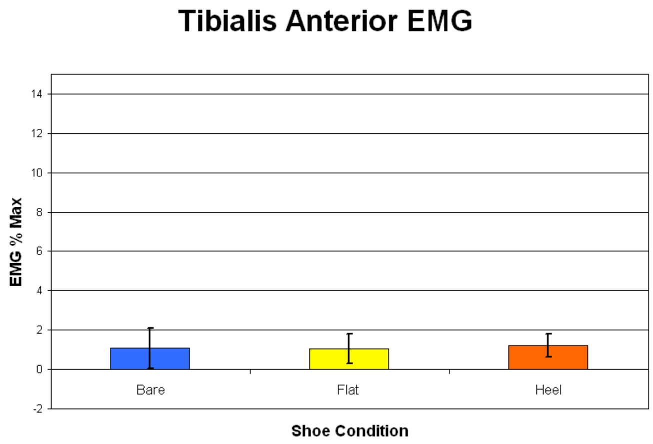
A two-way repeated measure, ANOVA, using Sigma Stat software was used to compare the biomechanical variables (kinematic, kinetic and EMG) between shoe conditions. When a significant difference was found, a Tukey post hoc analysis was performed. The level of significance was chosen as $p < 0.05$.

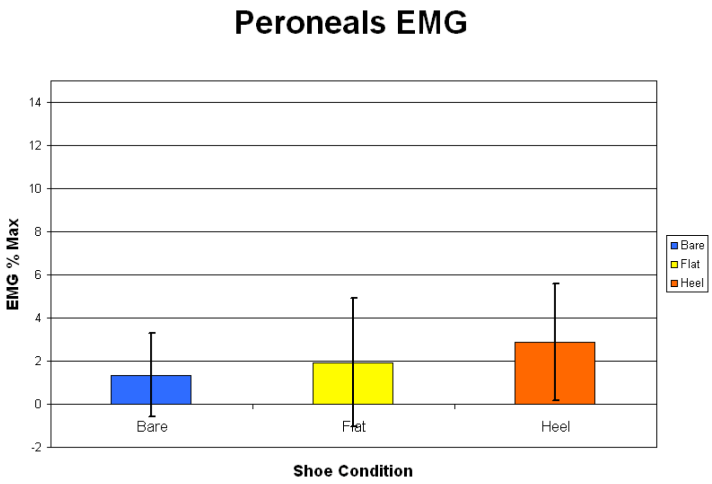
RESULTS

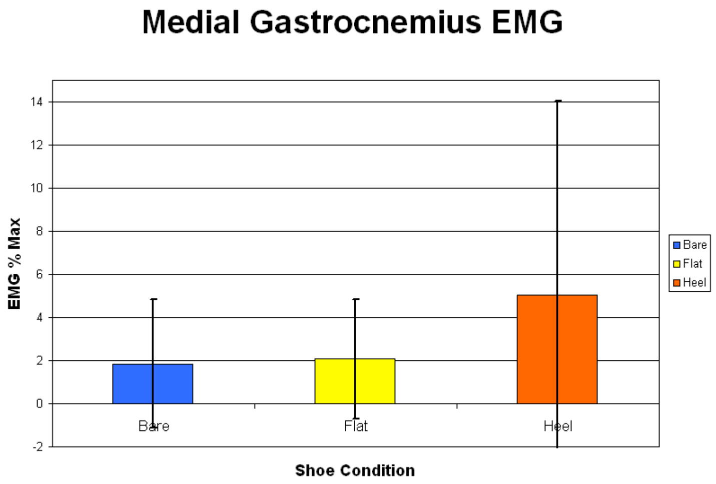
A one-way analysis of variance test (ANOVA) with repeated measures was performed to determine the effect of shoe condition on subtalar joint moment and activity in the tibialis anterior, peroneals, lateral gastrocnemius and medial gastrocnemius muscles for each subject.

Mean and standard deviation values of activity of each muscle considered for the shoe conditions of bare, flats and high heels are shown in table 1. There were no significant differences ($p < 0.050$) shown for muscle EMG for the tibialis anterior ($p = 0.883$), peroneals ($p = 0.077$), lateral gastrocnemius ($p = 0.093$) or medial gastrocnemius ($p = 0.330$).

ANOVA testing did reveal significant differences in subtalar joint moment between treatments (*p* = 0.006). Post-hoc mean comparisons (Tukey) were calculated for the factor of each shoe condition heel versus flat, heel versus bare and bare versus flat (table.2). Comparison showed the high-heeled condition to be different from both the bare and flat conditions with a significant difference of heel versus flat (*p* = .0.006) and heel versus bare (*p* = 0.028). No significant difference in mean value for subtalar joint moment was found for bare versus flat condition (0.501).







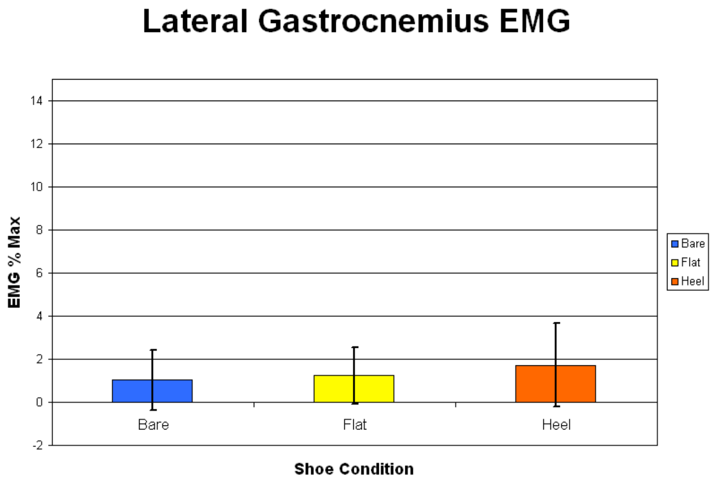


Table.1 - Mean and standard deviation of EMG activity of the tibialis anterior, peroneals, medial gastrocnemius and lateral gastrocnemius for each shoe condition.

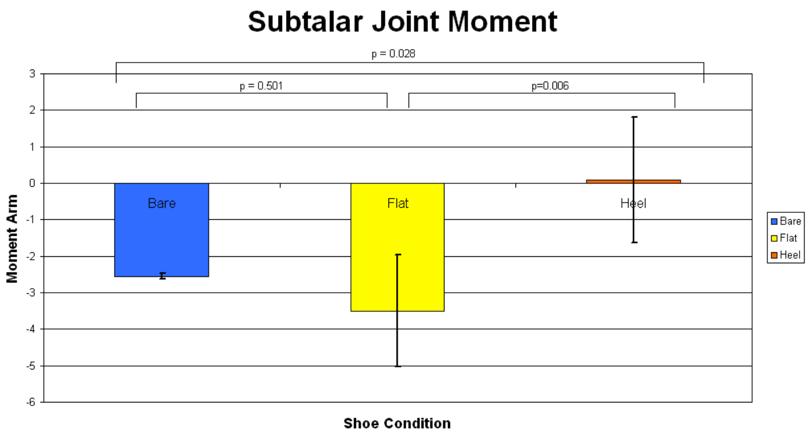


Table 2- Mean, standard deviation and post hoc statically *p* values of subtalar joint moments for shoe condition bare, flat and high heeled.

DISCUSSION

The study is purpose was to determine the action of the ground reaction force upon the heels of women standing in high-heeled shoes by looking at the anatomical difference about the subtalar joint axis. It was to bee determined where the ground reaction force acts relative to the subtalar joint axis and whether muscle activity while standing depends on this result.

Subtalar joint axis orientation was consistent with ranges reported by Isman and Inman (1969) with inclination ranges being within 20.5 degrees to 68.5 degrees and deviation ranges being within 4 degrees to 47degrees. Location of the subtalar joint axis had a fairly good repeatability from trial to trial within subjects. For example Subject #6 had only a four-degree standard deviation for both deviation angle and inclination angle. Subtalar joint axis orientation and repeatability could be due to the upward pull and placing the foot into a dorsiflexed position. This position locks that talocural joint so that the subtalar join axis is solely responsible for the side-to-side rocking motion about the ankle. Other non- invasive techniques to validate location of the subtalar joint axis are being tested and on the way.

Moments about the subtalar joint axis were significantly different. Significant difference (p=0.006) was found with comparison to high heels in the conditions of heel versus flats shoes (p=0.006) and heel versus barefoot (p=0.028). In general, while standing in high-heeled shoes women experience a small positive moment about the subtalar joint axis at the ankle. This positive moment causes an inverting torque experienced by women standing in high-heeled shoes. During barefoot and flat shoe conditions, a negative moment was seen resulting in a larger everting torque about the ankle.

All differences in EMG activity for the tibialis anterior, peroneals, lateral gastrocnemius and medial gastrocnemius were insignificant. However, two trends were seen in muscle activity by women while standing in high-heeled shoes. Similar to other studies, the first trend was that there was more muscle EMG activity of the tibialis anterior peroneals lateral gastrocnemius and medial gastrocnemius with increasing heel height. More specifically, a second trend was seen toward more activity in the high-heeled shoe condition for the peroneals and lateral gastrocnemius muscles. Both muscles showed close to significant results with the peroneals having p= 0.007 and lateral gastrocnemius having a p= 0.093.

Both the lateral gastrocnemius and peroneals are muscles that help eversion of the heel. The increase of activity of these muscles could have been a compensating response for the more positive- inverting moments of the ground reaction force while wearing high-heeled shoes. An increase in peroneal activity is similar to the data presented by Stefanyshyn et al., (2000). The increased activity of the peroneal muscle could be due to the controlling of the increased plantarflexion of the foot when standing in high heels. Another response to the increased activity of the peroneal is its role of protection to the foot from sudden inversion about the ankle and a stabilizer. The increased activity could be a required response, to stabilize the ankle joint when wearing high heels.

The response of the lateral gastrocnemius activity was similar to one other study conducted by Gefen et al. (2002), which showed the two heads of the gastrocnemius (lateral head and medial head) to respond differently when wearing high-heeled shoes. Other studies agree with no significant differences in EMG activity of the gastrocnemius (Stefanyshyn et al., 2000; Ono, 1969). While other studies showed a progressive negative linear relationship with increasing heel heights for EMG activity of the gastrocnemius (Lee et al., 1990). The explanation as to why a trend of activity of lateral gastrocnemius increased more in high heels versus that of the medial gastrocnemius is that the lateral head may act more intensively to produce the forces required to compensate the positive moment of the ground reaction forces. As seen in previous study resultant forces generated by the lateral gastrocnemius are transferred down to the Achilles tendon to the calcaneus. Since the foot is plantar flexed, the Achilles tendon is slackened and the lateral gastrocnemius helps to take up this slack, which could result in an inverting moment that acted to incline the foot's skeleton laterally. (Gefen et al., 2002)

EMG activity of the tibialis anterior was contradictory with results of some other studies. Studies conducted by Joseph (1968) and Lee et al. (1990) showed a decrease in EMG activity while standing in high heeled shoes. The tibialis anterior helps with dorsiflexion of the foot and acts as a stabilizer of the ankle. This study concluded while not significant a trend of increase muscle activity was seen in high heels for all muscles. Since the subjects were experienced high heel wearers they may no longer experience feelings of instability when wearing high heels. The increased EMG activity by the peroneals and lateral gastrocnemius seen to compensate for the inverting moment of standing in high heels could possibly not be seen with the tibialis anterior due to is location on the anterior aspect of the shank.

Limitations

Several limitations could have lead to the results of this study. All five subjects were college-aged women from the State College, Pennsylvania area. Subjects were also excluded if they did not wear a shoe size from 7, 7.5, 8, 8.5, to 9 comfortably since these were the shoes sizes provided by the researcher. Since the shoes were provided for the subject, new and unfamiliar shoes could have caused a limitation to the study. While EMG activities for all four muscles were insignificant a greater sample size could result in more significant results. Occasional burst of EMG amplitude potential from muscle of some subject while standing in high heels due to instability of posture was seen. Basmajian and Bentzon (1954) also found similar burst of activity in muscles accompanied by women wearing high heels. Placement of Eagle camera could also cause a limitation to this study. Eagle cameras were having difficulty tracking the motion of the marker located on the anteromedial aspect of the tibia and the lateral aspect of the calcaneus. Closer and more precise location of the camera could result in better accuracy of the subtalar joint axis location.

Future Research

Future research will include refining this study to test a greater sample sizes and to redefine the non-invasive method of the subtalar joint axis location to gather more précis data for analayzation. Other future plans are to test shoes with greater heel height than 2.5 cm to look at their effects and to look at the results of ground reaction forces about the subtalar joint axis in an individualized way from subject to subject. Future goals are to test a design of a biomechanical correct high heel shoe that accounts for anatomical differences of the joint axis.

Conclusions

Subtalar joint axis orientations were consistent with ranges reported by Isman and Inman, (1969) and subtalar joint axis location had fairly good repeatability. Moments about the subtalar joint axis were significantly different between the shoe conditions heel versus flat shoes, and between heels versus barefoot. High-heel shoes generally had a small positive inverting moment, but there was a larger everting moment in the barefoot and flat conditions seen. All differences in EMG activity for the tibialis anterior, peroneals, lateral gastrocnemius and medial gastrocnemius were insignificant, but with a trend toward more activity in the high-heeled condition for muscles that evert the heel (peroneals and lateral gastrocnemius). These muscles may have been compensating for the more inverting moments of the ground reaction force while wearing high-heeled shoes.

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