Plantar Pressure Distribution And Gait Stability: Normal VS High Heel

[1]Sharvindsing Karia,[2] S.Parasuraman,[3]M.K.A.Ahamed khan,[4]I.Elamvazuthi,
[5]Niranjan Debnath and [6]Syed Saad Azhar Ali
[1,2]Mechatronics, School of Engineering
Monash University Malaysia
Bandar Sunway, 46150, Malaysia
[3,5]Universiti Selangor,Faculty of Engineering
Kampus Bestari Jaya, Jalan Timur Tambahan
Selangor Darul Ehsan
[4,6]Dept. of Electrical and Electronic Engineering
Universiti Teknologi PETRONAS
Bandar SeriIskandar, 31750 Tronoh, Perak, Malaysia

Abstract*—In this paper, the plantar pressure distribution and the center of pressure movement were studied and gait stability of high heels versus normal heels was observed. A group of ten young female participants without any previous lower limbs injuries were asked to wear shoes of different heel heights, namely, 0cm, 2cm and 4cm and walk at a speed of 3km/hr on a treadmill. The pressure that their body exerts on the ground was recorded and analyzed. A statistical analysis was conducted and observed for the center of pressure ($p<0.05$), peak pressure ($p<0.05$) and the gait stability. The center of pressure moved from the heel to toe as heel height was increased and the peak pressure moved to the forefoot region. Tukey post-hoc analysis was performed in order to observe the differences in peak pressure in the forefoot, mid-foot and rear foot region. It was found that as the subjects wore a 4cm heel height shoes, the peak pressure was increased in the rear foot regions of the right foot. This resulted from the fact that they tend to lean on their right foot owing to instability during gait.

Keywords*— Center of Pressure, Plantar Pressure, Peak Pressure, High Heels.

I.INTRODUCTION

Women wear high heeled shoes on a daily basis either for work or for functions in order to enhance femininity and attractiveness. However, these high heeled shoes that they love so much can have negative effects on their body. These include bad body posture, shortening of the Achilles tendon, calf muscles shortening, instability while walking and also ankle sprain. The foot is a structure found in most vertebrates and it is the portion of a limb that bears the body weight and allows locomotion. In human beings, the most common motion is standing and walking and the plantar region of the foot is an important aspect. Figure 1 shows an image of the foot and its plantar region. The plantar foot consists of the plantar fascia which is a thick connective tissue which supports the arch on the bottom of the foot and the calcaneus. The calcaneus is, also known as the heel bone, which constitutes the heel. It is also the largest bone of the foot. The plantar fascia acts as an elastic spring when the body is acting on it and causes the body to be stable when a person is standing normally. It also has a critical role in the normal mechanical function of the foot during normal gait [1]. The plantar foot also represents the configuration of the feet, biomedical functions of the feet, legs and even the whole body [2].

A. Plantar Pressure measurement

Foot plantar pressure is the pressure field that acts between the foot and a supporting surface. This pressure is distributed across the plantar surface of the foot [3]. Figure 4 shows an image of the plantar region of the foot and the pressure exerted. The scale provided quantifies the pressure exerted. This pressure can be further resolved to a point on the plantar region called the center of pressure. This point is the location where all the pressure is concentrated. The center of pressure can move in both X and Y direction.

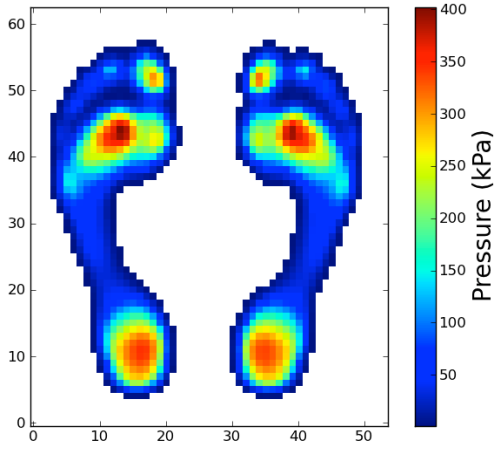

Figure 1: Plantar pressure Measurement

After 2000, researchers have been reported on athletic plantar pressure measurement and analysis in order to improve sports

performance and achievements [4]. Some sports include soccer, swimming, cycling, rugby and baseball[5]. Plantar pressure distribution varies also in people wearing high heel shoes. However, these shoes have some considerable negative effects to their users. 39% - 69% of women wear high heel shoes on a daily basis and recent studies have revealed that people judged women wearing high heel shoes to be more attractive than those wearing flat shoes[6]. High heel shoes are also associated with increased risk of falls, and also risk of getting disorders such as plantar fasciitis, ankle sprain and chronic low back pain over time[6].

II. METHODS

A. Experiments

A group of healthy female participants were selected to perform the experiment. The moticon sensor was inserted inside the shoes and the participants were asked to wear them. The sensors were then switched to recording mode. The subjects were then asked to stand straight normally (at rest position) for a period of 10 seconds and then they were asked to walk on a treadmill whose speed was set to 3km/hr. This was done for a period of 40 seconds. After 40 seconds, the participant was asked to remove the shoe and the sensors were switched back to normal mode. The data stored in the memory of the sensors were then downloaded to a computer for processing. This was repeated for all three heel heights, that is, 2cm and 4cm. Figure 2 shows the different shoes used in this experiment. The first shoe has heel height of 0cm and the others have heel height of 2cms and 4cms respectively.

Figure 2: Shoes of Different Heel Heights

B. Subjects

The experiment was conducted using a group (10 subjects) of young and healthy female participants. All the participants were reported to have no present or past leg or foot injuries and zero musculoskeletal disorders that could restrict their motion while doing the experiment. Any disorders might make the wearing of the high heeled shoes painful during the experiment. The participants were also reported to be wearing high heeled shoes very often which would make them more comfortable and also reduce the amount of human error during the data recording.

Table 1 Demographic characteristics of the 10 participants.

Demographics	***Young Participants***
Age (yrs.)	21 ± 1.5
Height (m)	1.50 ± 0.07
Mass (kg)	60 ± 8.0
BMI	23 ± 2.0
Shoe Size (UK)	7
Leg Length (m)	0.87 ± 0.04

Mean ± SD, NSW – Normal Walking speed, BMI- Body Mass Index

C. Analysis Of variance (ANOVA)

Statistical analysis can be applied in many situations in our everyday lives. It is relevant in many field of study such as engineering, business, natural science and many more. Analysis of variance (ANOVA) is one of the topics taught in statistics curriculum. ANOVA is carried out in two ways. One is the One-Way ANOVA and the second is the Two-Way ANOVA. However, in this study, One-Way ANOVA will be used. One-Way ANOVA is the analysis of variance as the name states and is used to test hypotheses. The hypothesis states that the means of all populations are equal and have the same variance, σ^2. The test is carried out by calculating two estimates of the variance of the population distribution namely, the variance between groups and variance within groups. The variance between groups is also known as the mean square between samples (MSB) and the variance within groups is known as mean square within samples (MSW). If the means of the samples is not equal, a large variation of the MSB is expected among the samples. The test statistic, F, for the analysis of variance is calculated as follows:

$$F = \frac{Variance\ Between\ Samples}{Variance\ Within\ Samples} = \frac{MSB}{MSW}$$

The test statistics has the F distribution with two degrees of freedom, $k-1$ and $n-k$ where k is the number of samples and n is the number of data values in all samples.

D. Statistical Analysis

Statistical significance is attained given that the p-value obtained is less than the significance level. The significance level is often denoted as α and is set to 5% (0.05). It is the probability of rejecting the null hypothesis given that it is true. The p-value is the probability of obtaining extreme results given that the null hypothesis is true. In this study, the Tukey post-hoc analysis is performed. If the p value is less than α, the null hypothesis is rejected.

E. Acquisition

Data was recorded using the Moticon sensor insole consisting of capacitive sensors. . Firstly, the participant is asked to step onto a treadmill while wearing the shoes containing the insoles and standstill for ten seconds. The data recorded during these ten seconds will be processed for the analysis of the center of pressure and peak pressure. After the ten seconds, the treadmill is set to a speed of 3 km/h and the participant starts walking with a good posture. This is because this speed is the normal speed of the human gait. The human gait is the locomotion achieved by the movement of the lower limbs of

the human body, which in this case refers to the normal walking of the participant.

Figure 3: Moticon Sensor

The pressure is recorded while the participant is walking for a period of 20 seconds in order to analyze the displacement of the center of pressure. In this process, the data is recorded at a sampling rate of 50Hz.
After the recording process is complete, the insoles are again connected to the software. The recorded data is then downloaded from the insoles and saved into a text file which can be used for analysis. The data obtained from the Moticon sensor was downloaded to a computer and was processed using IBM SPSS statistical software where one-way analysis of variance and *Tukey* post-hoc analysis was performed ($p<0.05$).

III. RESULTS

The plantar region of the foot is divided into three regions. These are the forefoot, mid-foot and rear foot as shown in Figure 4. From the data obtained, the pressure distribution was observed in all three regions. The pressure values of all the subjects was taken and the average and peak pressure was determined.

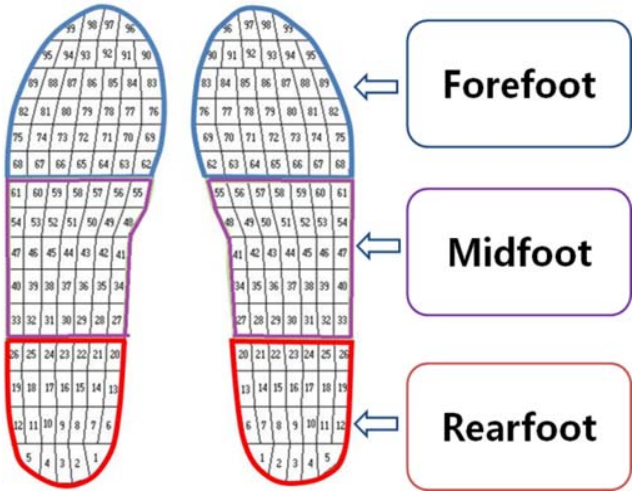

Figure 4: Plantar Regions

A. Center of Pressure

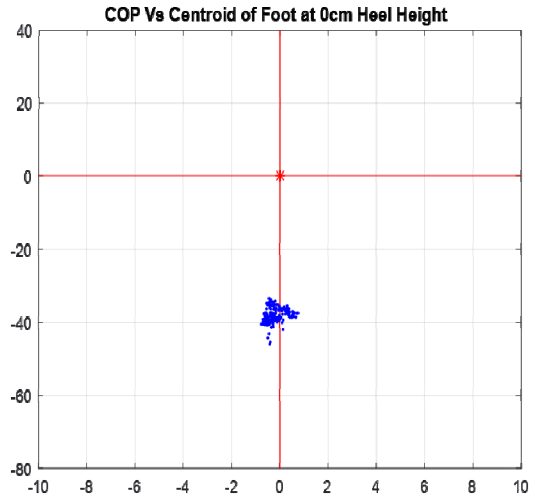

Figure 5: Center of Pressure VS Centroid at 0cm Heel height

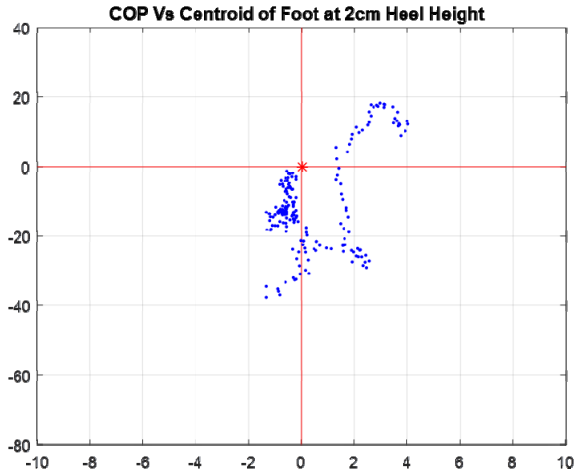

Figure 6: Center of Pressure VS Centroid at 2cm Heel Height

Figure 5, 6 and 7 shows the center of pressure location compared to the centroid of the foot at heel height of 0cm, 2cm and 4cm respectively. The red intersection represents the centroid of the foot.

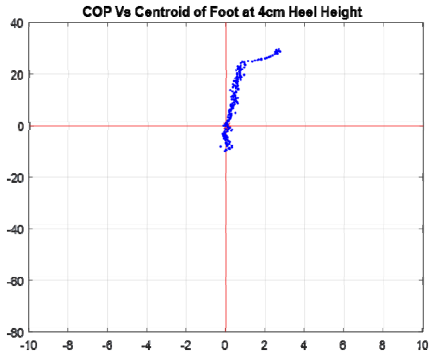

Figure 7: Center of Pressure Vs Centroid at 4cm Heel Height

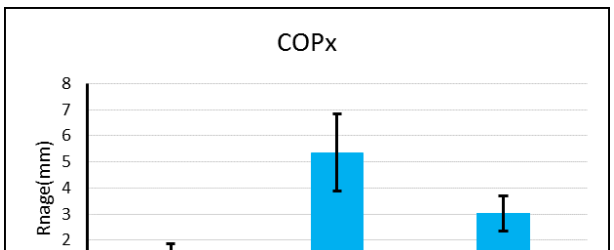

Figure 8: Range of COPx

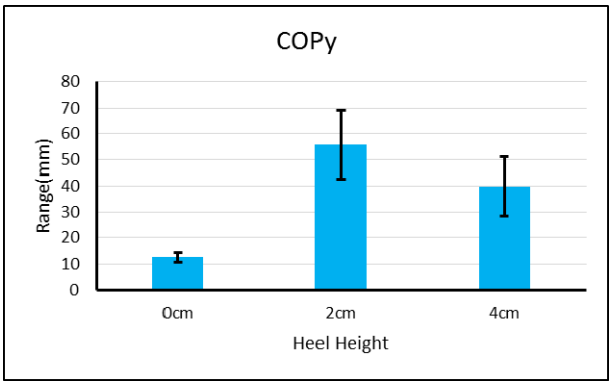

Figure 9: Range of COPy

Figure 6 and 7 shows the range of the center of pressure in the X and Y direction.

B. Peak Pressure

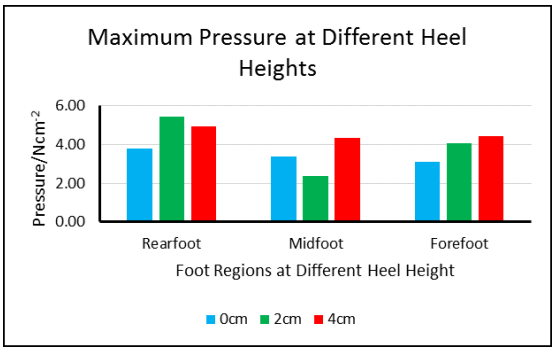

Figure 10: Peak Pressure at Different Heel Heights and Foot Regions

Figure 10 shows the peak pressures at the different regions of the foot using different heel heights.

IV. DISCUSSION

The range of the center of pressure along the Y direction also differed. At 2cm heel height, the range of the center of pressure increased and had a larger standard deviation than the range of 0cm. However, at 4cm heel height, the range decreased and had almost the same standard deviation as heel height of 2cm. This can be seen from figure 9.

However, the center of pressure along the X direction was also observed to be changing as observed from figure 6. At 0 cm heel height, the center of pressure did not show much variation and had a very small standard deviation. At heel height of 2cm, the range increased by twice the amount and had a greater standard deviation. Moreover, at heel height of 4cm, the range dropped along with the standard deviation. This resulted from the fact that at heel height of 4cm, the subjects tend to lean on the right foot, thus, caused the center of pressure to move along the X direction as well.

From the analysis of variance of the center of pressure, the F value calculated exceeds the $F_{critical}$ where it is set at 3.01. This showed that there is a difference between the means peak pressure at different heel heights. This is shown in figure 11.

	F value
Left COPy	1121.373
Left COPx	32.822
Right COPy	2053.148
Right COPx	405.553

Figure 11: Analysis of Variance for Center of Pressure

Moreover, the p value calculated using the *Tukey* post-hoc analysis software is less than the threshold, α for the center of pressure in the Y direction. However, the p value exceeds the threshold between 2cm and 4cm heel height in the mean value of the center of pressure in the X direction. Between these two heel heights, the subjects started to lean on their right foot resulting from loss of stability while walking.

I sample	***J sample***	***Mean Diff***	***P***
0cm	2cm	-27.361	0.000
	4cm	-47.901	0.000
2cm	0cm	27.361	0.000
	4cm	-20.540	0.000
4cm	0cm	47.901	0.000
	2cm	20.540	0.000

Figure 12: Statistical Analysis of COPy for Left Foot

I sample	***J sample***	***Mean Diff***	***P***

I sample	*J sample*	*Mean Diff*	*P*
0cm	2cm	-7.480	0.000
	4cm	-46.990	0.000
2cm	0cm	7.480	0.000
	4cm	-39.511	0.000
4cm	0cm	46.990	0.000
	2cm	39.511	0.000

Table 13: Statistical Analysis of COPy for Right Foot

The peak pressure at the different regions, namely, the forefoot, mid-foot and rear foot was observed as shown in figure 8. At 0cm heel height, the data showed that the peak pressure was almost uniformly distributed in the three regions mentioned earlier. As heel height increased, the peak pressure at the different regions changed

At 2cm the peak pressure at the rear foot region increased compared to the peak pressure at 0cm heel height and at 4cm, the peak pressure decreased by a small amount. At the mid-foot region, the peak pressure decreased and then was higher at 4cm heel height. This is because the shoe consisted of a soft and thick sole compared to the other shoes. The 4cm heel height shoes provided support to the arch of the foot which allowed the pressure in the mid-foot region to be well distributed, hence, improving the recording process of the sensors.

However, at the forefoot region, the pressure increased with heel height. This is because as the height increased, the center of gravity if the subjects moved forward and therefore a greater pressure is exerted on the forefoot region compared to the mid-foot and rear foot.

The analysis of variance of the peak pressure indicates that the F value calculated exceeds the $f_{critical}$ (3.01) in all three regions where the analysis was conducted. It was also found that this value was greater in the rear foot region of the right foot compared to the left foot. This shows that the pressure exerted in that region as heel height was higher and explains the tendency of the subjects to lean on the right foot during normal gait. This is shown in figure 14.

	F value
Left Forefoot	43.273
Left Mid-foot	270.309
Left Rear-foot	13.781
Right Forefoot	30.653
Right Mid-foot	287.715
Right Rear-foot	74.549

Table 14: Analysis of Variance for Mean Pressure

The *Tukey* post-hoc analysis of the peak pressure also indicated a difference between the peak pressures in the different regions with a p value of less than the significance level of 0.05. Between the mid-foot and rear foot area of the right foot, the p value exceeded the significance level.

IV. CONCLUSION

The plantar pressure distribution analysis is an advanced subject in the field of engineering which is concerned with more and more people nowadays. From the results gathered, the center of pressure is observed to be moving from the rear foot region to the forefoot region and the range in which it moves also increases with increasing heel height. The peak pressure recorded at the forefoot region also increases as heel height increases. From the analysis of variance (ANOVA), there is a significant difference between the peak pressures at the different regions at the three heel heights. The Tukey post-hoc analysis showed that the pressure increased at the rear foot region of the right foot as the subjects tend to lean on that foot due to the instability of the high heel shoes. Some improvements have to be made in this experiment in order to analyze the center of pressure and gait stability by increasing the number of subjects and by putting them in different groups. Better results might be obtained by using the two-way analysis of variance when putting the participants in different groups. To conclude, the plantar pressure analysis can be further used in the design of shock absorption insoles and also in the design of orthopedic shoes and not to forget the corrections in the gait of human beings.

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