# Plantar Force Distribution for Increasing Heel Height Within Women's Shoes

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Women have sacrificed foot comfort for fashion dating all of the way back to 1700 BC when women of the Shang dynasty bound their feet [10]. Present day women wear towering stiletto heels that are notoriously known for being uncomfortable. Within my study I sewed 10 *Force Sensing Resistors* made by Interlink Electronics onto the base of a nylon sock. This nylon sock was worn inside of different shoes of various heel heights. A digital multimeter read force readings from each sensor while I was standing in a static stance. The overall percent of force on each sensor was calculated and the data suggested that as heel height increased the point with the highest force, which was on the ball of the foot, also increased. It also suggested that as heel height increased the force on the middle of the foot would also increase. This displays a redistribution of force towards the front of the foot as heel height increases. This percentage of force shows different results since less overall force was measured for the data runs with high heeled shoes.

## I. INTRODUCTION AND THEORY

The first physics problem I ever remember doing was in Mrs. Geitz's eighth grade science class. We compared the pressure exerted by a full grown elephant on it's four feet to the pressure exerted by a pair of stiletto heels. To my surprise I found that I would rather be stepped on by an elephant than a woman wearing heels. Ever since then I have worn many different kinds of shoes and a pair of high heels has never felt the same as my favorite pair of sneakers.

Women's footwear has been the focus of multiple studies. As stated in Caroline M. Speksnijider's [1] article *The higher the heel the higher the forefoot-pressure in ten healthy women* 83% of women ages 50-70 who wear high-heeled shoes report foot problems [1]. One study showed that 37-69% of women wear high-heeled shoes on a daily basis [2]. The quest to find a more comfortable high heel shoe is not a goal just for the medical industry. Shoe designers have been trying to design heels that are comfortable to wear. Recently Gordon Thompson III, a tennis shoe designer, left Nike to design comfortable women's dress shoes for Cole Haan. The Cole Haan shoes contains Nike's "Zoom", which is a system of air bags that are filled with air and a fiber made from wood pulp cellulose, called Tencel. Costumers are willing to pay upwards of around $300 for a more comfortable shoe, so there is a large market to whomever can design and produce the most comfortable high-heel shoe [3].

One of the main discomforts while wearing heels is the impact force that is created when the heel strikes the ground. When this occurs the impact force travels not only to the foot, but up the legs and into the back [2]. There have been multiple studies that analyze the force and pressure distribution for various kinds of footwear. Joanne R. Eisenhardt [4] conducted a study that analyzed how changes in heel heights affected walking gait characteristics and pressure distribution. This study found that when women wear high-heels the stance phase of the walking gait is elongated, when compared to walking barefoot. However the time spent in the stance phase did not change for the height of the heel. Pressure on the fifth metatarsal, also known as the "little toe", is the only area of the foot that is directly affected by heel height. While wearing no shoes the fifth metatarsal sustains greater peak pressure than compared to wearing any heeled shoes [4]. This may suggest that as heeled shoes are worn the pressure that was originally placed on the fifth metatarsal is displaced to somewhere else within the foot.

Y. Cong [5] did a study on how the thickness of the shank curve effects the plantar pressure distribution. Plantar pressure is the pressure on the base of the foot and the shank curve is the part of the shoe between the heel and ball of the foot, that supports the arch of the foot. Within his study four women wore three different shoes with varying shank curve thicknesses of five, eight, and eleven millimeters. The women would walk in the different shoes and their peak pressures were measured for the three main areas of the foot; forefoot, midfoot, and rearfoot. The rearfoot showed little difference in peak pressures for the varying shank curves. The forefoot showed a slight decrease in peak pressure for an increase in shank curves thickness, but the greatest change in peak pressure was in the midfoot region. As the shank curve thickness increased, so did the peak pressure. The reasoning behind this is that when there is extra arch support the shank acts like part of the heel. As the person wears the shoe with the greatest shank curve, it stops the foot from sliding forward, thus a greater weight is placed on the midfoot, instead of the forefoot. This makes sense because if there was a decrease in the forefoot pressure, the pressure had to be placed somewhere else [5].

Many studies, when analyzing the affect of various shoes on plantar pressure, usually collect data while the shoe is in motion. D. Rosenbaum [6] conducted a study where participants plantar pressure distributions were analyzed for different speeds of walking. The participants walked at what they thought were a slow, medium, and fast walking pace. As walking speeds increase, the study found that the peak pressure for the heel and medial area of the forefoot increased significantly. While the midfoot and lateral forefoot peak pressures decrease [6]. This shows that the speed of a participant's walking does effect the peak pressure and should be taken into account for other studies.

A study was done with different insoles to see if there was a relationship between plantar pressure distribution and insole comfort. An *EMED* pressure-measuring insole was placed inside of 14 different men's running shoes. Four different insoles were placed in the participants shoes and they were asked to run and walk on a treadmill with the various insoles. The participants were asked to rank the comfort of each of the insoles. The most comfortable insole created higher pressures in the midfoot area and lower pressures in the medial forefoot and hallux (big toe) areas. This insole that was rated the most comfortable provided an even distribution of force throughout the entire foot. The least comfortable insole provided the greatest force distribution in the medial forefoot and hallux region, which took force off of the rearfoot. This study suggests that the pressure distribution along the sole of the foot can provide insight on what is comfortable for shoes. This can be used in designing future shoes to be more comfortable to wear [7]

My project focused on the force exerted by gravity and the mass of my body onto various areas of my foot, while wearing different high-heeled shoes. As heel heights increase, the toes stay relatively parallel to the ground. One would assume that this alignment would create a large force on the toes, since the body wants to travel in the downward sloping direction in which the feet are aligned. From experience, I know that high-heel shoes are very uncomfortable. After wearing some shoes for an hour the ball of my foot, more specifically the area below where my toes begin becomes painful. Since this is a joint, the foot is able to bend at this position and the foot no longer slopes starting in this area. I predict that the extra pressure exerted from the mass of my body and the downward slopping heel, causes this area to hurt more than others.

To test this prediction a force measuring device had to be made. Within journal articles one of the most common systems to measure plantar force and pressure distribution was the *Pedar* system. This system contains a light weight sock that contains up to 1024 sensors. This system enables the maximum amount of mobility since the sensors are attached wirelessly to a computer which collects the data [8]. This would have been the ideal way to measure plantar force distribution for my Junior Independent Study, but the system was out of the price range allotted for this project. Another study done by R. W. Soames used small semiconductor strain gauge transducers to measure the force exerted on various areas of the foot, including each individual toe [9].

Strain gauges can be fairly inexpensive, this made them an ideal way to measure force distribution for my experiment. We purchased *Force Sensing Resistors*, also known as FSRs from Interlink Electronics [11]. These were circular sensors with a 1/2 in. diameter, that would provide a resistance for various forces that are exerted on them. They are lightweight and thin which made them ideal to wear inside of a shoe. The relationship between resistance and force was provided as a graph in the FSR manual [11], Fig. 1. This graph has a power-law relationship and using this data we were able to convert the resistances to forces.

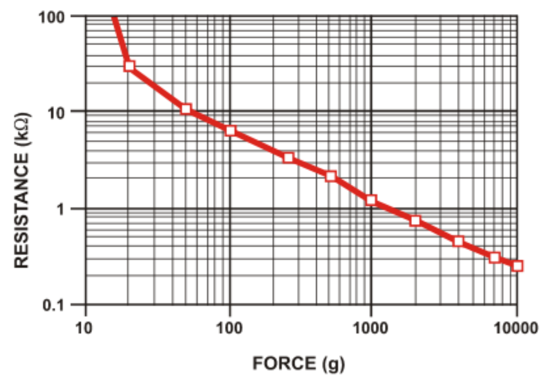


FIG. 1: This is the graph provided by Interlink Electronics [11] that provides the relationship between resistance and mass in grams for the FSR sensors.

## II. EXPERIMENTAL

In order to measure the force exerted on different areas of a foot while standing, different force sensors had to be placed on various parts of the sole of the foot. Ten *Force Sensing Resistors* made by Interlink Electronics were sewn to a sheer nylon sock. The arrangement of these sensors is shown in Fig. 2. Through a series of wires the sensors were connected to the rear of a *Keithley 2000 Multimeter*. The signal from the multimeter was sent to a *National Instruments GPIB-ENET/100*, which then sent the data acquired to a computer running a *LabVIEW* program.

The program collected a reading from each sensor sequentially and displayed the resistance value. A specific heel height was used for each data run. The vertical distance between where the bottom of the heel and the bottom of toes were positioned was measured for each shoe, this is known as the heel height. Take note that the heel height did not take into account any platform or extra sole that was beneath the toes. Once this heel height was recorded, the shoe was slipped onto the foot, that was already wearing the nylon sock with sensors.

Once the sensors were aligned I stood in the heels with my knees locked. I stood as naturally as I could while wearing the shoes in order to not create any biased data. The *LabVIEW* program ran for two minutes while it collected data. This data was then uploaded into *Igor Pro* to be analyzed. This procedure was repeated for bare-feet,

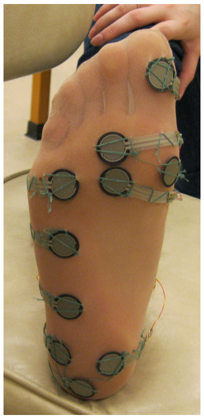

FIG. 2: This is a photograph of the sensor sock made for this experiment.

one pair of flats, and four high heel shoes with various heel heights.

In order to convert the resistances given by the FSR sensors to a force, I had to find an equation to match the power-law relationship. I tested the calibration curve for all of the sensors. The data from the FSR graph was appended to the graph of collected data to compare results, Fig. 3. As the masses increased the resistances we found were more like the resistances given within the FSR graph. Since we assumed that the mass applied to the sensors when I was wearing them were going to be at least 0.5 kg or higher, the FSR data was acceptable to use. Therefore we assumed that the resistance versus force graph given in the FSR manual [11] was acceptable to use for our sensors.

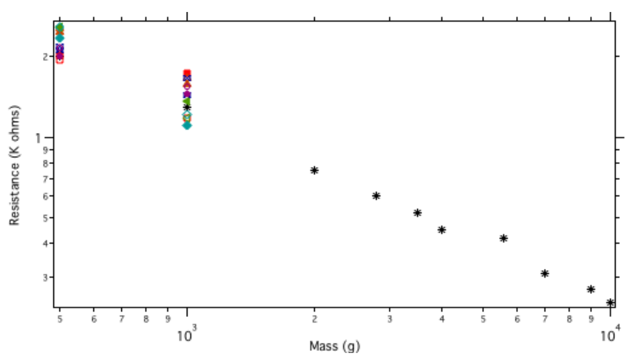


FIG. 3: This is the graph containing the FSR data and the resistances and masses collected from three different sensors.

I measured the x and y coordinates from the graph in Fig. 1 and graphed it again in *Igor Pro* on a mass (g) versus resistance (k ohms) log-log plot. I did a weighted fit to the data to find the equation to convert resistance to force by converting to kg and multiplying by the acceleration due to gravity; this relationship is

$$F(N) = (10^3)(9.81m/s^2)(1343 \pm 64)(R(k\Omega))^{-1.415 \pm 0.037}. \quad (1)$$

## III. RESULTS

The data taken from all of the different data runs were uploaded into *Igor Pro*. The resistance for each sensor was averaged and the standard deviation was found. The average resistance was converted into force by Eq. 1. To display the force for each sensor, an outline of the right foot was made with circles that represent the approximate position of each sensor. The circles contain numbers that represent the corresponding sensor. The sensors are also color coded to represent the force exerted on each sensor. All of the runs are shown in Fig. 4 with the color coding. Some of the sensors are left blank on the inside, this indicates that the sensor did not read properly for the run. A diagram was made to show the percent of force that was registered by each sensor when compared to the force measured by the complete set of ten sensors. This diagram is shown in Fig. 5.

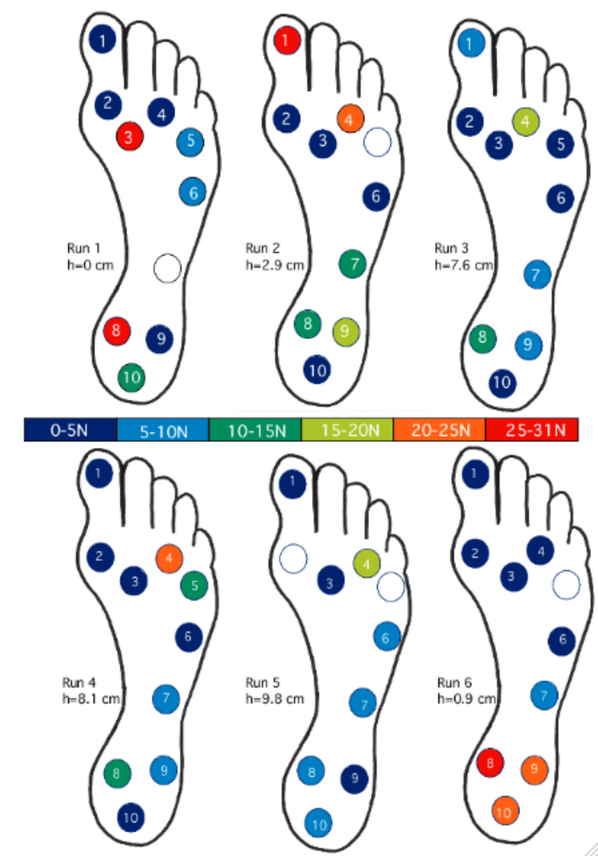


FIG. 4: This image shows all six different runs and the general idea of where the forces were displaced.

## IV. ANALYSIS AND DISCUSSION

The data runs with the greatest forces on different areas of the foot are runs one and six. This seems odd since run one took data while no shoes were worn and

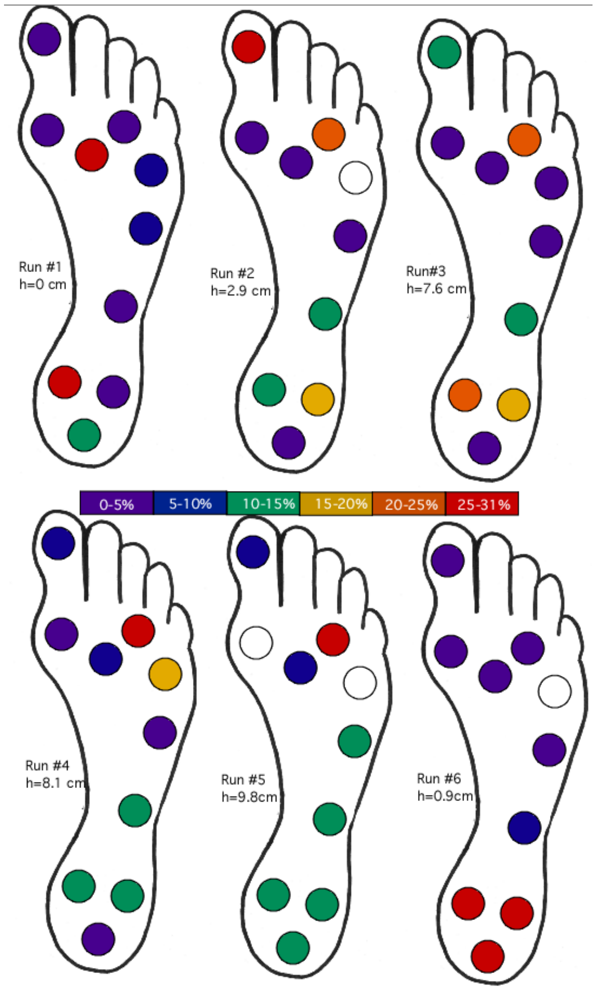


FIG. 5: This image shows all six different runs and the percent of the overall force that was registered by each sensor.

run six took data while wearing Sperrys, which are flats and have an almost negligible heel height. The largest heel height of 9.8±0.1 cm doesn't show a large force on any part of the foot relative to the other data runs. I find this strange since the data suggests that being barefoot or wearing flats would be more painful than wearing nearly any size heeled shoe. If we assume that high forces cause foot discomfort and from personal experience I do not think this is accurate.

To look at the data in another way the percentage of each sensor to the total force of all of the sensors was found. This average enabled us to see if there was a difference between the forces that seemed similar by the color coding in Fig. 4. While looking at Fig. 5 we see that as heel height increases, more of the force is placed on the mid-foot or arch of the foot. This seems to agree with my intuition since the downward sloping angle of the shoe would cause the foot to position more of its force towards the front of the shoe and not on the heel. We can also note that the largest percentage of force is located on the ball or toe of the foot for increasing heel height. In Fig. 5 for run three, the orange sensor on the ball of the foot is a percentage of 28% and the sensor on the heel of the foot has a percentage of 24%. This data suggests that as the heel height increases the percent force shifts towards the front of the foot. When the data is analyzed this way, it correlates more with the general consensus that high heels are more uncomfortable than flats or being barefoot.

The human body is genetically designed to be able to walk barefoot. Even though there was a high force concentration on the heel and ball of the foot, maybe the discomfort of the force is not noticed because humans are biologically designed to withstand forces in that area better than other areas of the foot. The body may not be designed to have large forces in other areas of the foot. This could explain the discomfort for high-heels with smaller forces in other areas and greater comfort for being barefoot or wearing flats with larger forces.

There are several flaws with my experiment. For my experiment the sock was connected to a multimeter via wires. When the shoes were placed on my feet, I was able to stand, but I was not able to walk around and have my feet really mold into the shoes. Other studies collected data while the participant was walking or running. My apparatus did not allow for me to do this. When walking, different parts of the foot make contact with the ground at different times. This causes a greater pressure or force if there is less area to absorb the downward force of the body. This may cause greater pressure in higher heel heights on the parts of the foot in contact with the ground.

When the shoe was placed over the sock sometimes there was difficulties getting the sensors to easily slide in. This could have led to poor wire connections and sensor damage. I believe that the sensors that are colored in white in Fig. 4 did not register a resistance due to a bad connection. The data runs that had the least overall sum of forces were the runs that contained high-heeled shoes. Runs three and five, which had the least summation of force, were from shoes that contained many straps that ran across the top of the foot where the sensor wires were. This could have caused excess pressure on the wires or movement of the sensors while wearing the shoe.

High-heeled shoes are also uncomfortable due to other factors just than the force exerted on different areas of the foot. From personal experience I know that shoes with tall heels that do not cover the entire foot can easily cause blisters which are very uncomfortable. The foot also has to contract and the toes will curl just to ensure that the shoe does not come off of the foot while walking. Sometimes the downward slope can cause the foot to move into the front of the shoe when there may not be room for the foot, which can be painful. So even though the data in Fig. 4 may not directly show that high heels can be uncomfortable, there are still other reasons why they are uncomfortable.

## V. CONCLUSION

Plantar force distribution was measured with FSR sensors for shoes with different heel heights, while standing. The forces collected and analyzed suggested that standing barefoot or wearing flats places more force on the heel and ball of the foot rather than a pair of high-heeled shoes. When heel height increased the FSR sensors did not show an increase in force. When the percent of force exerted on the different areas of the foot we analyzed, as heel height increased the percent of force exerted on the mid-foot also increased. The greatest percentage of force while wearing heels was located in the ball of the foot and increased as heel height increased. It was also noted that as heel height increased the percentage of force exerted on the sensors located on the middle of the foot would also increase. This data shows a different trend from the raw force values, since less total force was recorded as heel height increased. It appeared that there was a greater total force for shoes with lower heel heights or being barefoot. Maybe this suggests that when I was barefoot there was a greater force concentration in the areas where the sensors were placed, compared to wearing high heels.

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[1] Caroline M. Speksnigder, Rieny J.H. vd Munckhof, Sjors A.F.C.M Moonen, Geert H.I.M Walenkamp, "The higher the heel the forefoot-pressure in ten healthy women," The Foot, 15, 17-21 (2005).

[2] Lee Yung-Hui, Hong Wei-Hsien, "Effects of shoe inserts and heel height on foot pressure, impact force, and perceived comfort during walking," Applied Ergonomics, 36, 355-362 (2005).

[3] Pitz, Marylynne. "Nike's Air System Slips into High Heels," Pittsburgh Post-Gazette (2006).

[4] Eisenhardt, Joanne R., Deneen Cook, Ingrid Pregler, and Henry C. Foehl. "Changes in Temporal Gait Characteristics and Pressure Distribution for Bare Feet versus Various Heel Heights," Gait and Posture 4, 280-286 (1996).

[5] Cong, Y., Y. Luximon, and M. Zhang. "Effect of Shank Curve of High-Heeled Shoe on the Plantar Pressure Distribution," APCMBE Proceedings, 500-502 (2008).

[6] Rosenbaum, D., S. Hautmann, M. Gold, and L. Claes. "Effects of Walking Speed on Plantar Pressure Patterns and Hindfoot Angular Motion," Gait and Posture 2, 191-197 (1994).

[7] Chen, H., B. M. Nigg, and J. De Koning. "Relationship between Plantar Pressure Distribution under the Foot and Insole Comfort," Clininical Biomechanics, 335-341 (1994).

[8] "Novel Product Info - Pedar,"http://novel.de/productinfo/systems-pedar.htm.

[9] Soames, R. "Foot Pressure Patterns during Gait," Journal of Biomedical Engineering 7, 120-126 (1985).

[10] Lim, Louisa. "Painful Memories for China's Footbinding Survivors," http://www.npr.org/templates/story/story.php?storyId=8966942

[11] "Force Sensing Resistors An Overview of the Technology," Interlink Electronics.