SMART DRESS SHOES WITH AUTOMATICALLY ADJUSTABLE HEEL HEIGHT AND ANGLE OF SHOES

A Thesis

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Master of Arts

by

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ABSTRACT

High-heeled shoe design creates ergonomic challenges in regard to the comfort of women's feet. While previous studies have focused on the effects of heel height and weight distribution of high-heeled shoes, no study has attempted to determine the effectiveness of an adjustable heel height system with an automatically rotating outsole. However, using pressure distribution data, improvements can be made to significantly increase the comfort, as well as the qualitative statements of comfort, for high-heel comfort.

The purpose of this study is to evaluate the hypothesis that 1) the adjustable heel height system will relieve pain on the ball of the foot by adjusting the load between the forefoot and the heel, and 2) an automatically rotating outsole will prevent pain on the ball of the foot by redistributing the load from the wearer's forefoot to their mid-foot and heel. According to qualitative data, a new high-heel shoe design is proposed to improve foot comfort by 58.5% as compared to traditional high heels. The data also shows that, in comparison to conventional high-heeled shoes, the new design reduces the average peak pressure of each subject's forefoot region by 50.3%, and increases the pressure of the mid-foot and heel (when standing) by 31% and 34%, respectively. It also shows that the proposed design reduces, on average, the peak pressure of the subject's fore-foot region by 34%, and increases the pressure of the mid-foot by 32%, and the heel by 52% during walking task. These results highlight the importance of redistributing plantar pressure on the fore-foot, mid-foot, and heel regions while women wear high-heeled shoes.

BIOGRAPHICAL SKETCH

David Shi obtained his Bachelor of Arts degree in Fashion Design at DongHua University. He moved to Milan, Italy to continue his studies in the luxury industry in 2012. With the aim of integrating fashion and technology, he moved to the United States in 2014 to pursue his Master of Arts in Apparel Design at Cornell University where he will begin his Ph.D studies in the Fall of 2016.

ACKNOWLEDGMENTS

This study would not be possible without the support from my advisor, Prof. Huiju Park, who has always guided me in the right direction at the right time. Nor would my research be accomplished without the support from my parents. Also, Professor Robert Shepherd for his advice on designing and building soft robotics systems.

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PREFACE

This work is organized in five chapters. Chapter 1 explains the background of high heel pain and introduces a new design approach to solve the problem of high heel pain. Chapter 2 is a literature review of high heels research in detail. Chapter 3 explains the methodology of designing and testing the proposed high heels in detail. Chapter 4 discusses the test results of the proposed design. Finally, Chapter 5 discusses the conclusion.

CHAPTER 1

INTRODUCTION

1.1 Pain while wearing high-heeled shoes

Foot pain by wearing high heels is a common problem among women. New York Times reports that about 75% of people in the United States have foot pain, which a large portion can be attributed to women wearing high heel shoes (New York Times, 2008). High heel shoes are known to cause pain, in particular to the balls of wearer's feet. In addition, according to statisticbrain.com, women's dress shoes account for about 35% of the overall women's shoes market (Statistic Brain, 2015). This ranks dress shoes as the number two category of women's shoes (women's casual shoes is ranked first, occupying 42.5% of the market).

High-heeled shoes are known to produce adverse effects to women. According to the research from the history of medical scientists on high heels conducted by Kouchi (2000) and Linder (1998), the medical experts in the past warned about the potential health issues of wearing high heels since 250 years ago.

It is reported that wearing high heels has the following negative effects: 1) Ball of foot pain 2) Corns and bunions 3) Risk of ankle sprain 4) Low back pain, and 5) Leg muscle fatigue (Daily Mail, 2013). All five of these problems are long-term effects, which could cause the serious health issues to people who wear high-heeled shoes.

1.2 The design solution for high heel pain

High-heeled shoes have been created to make female's calves look slimmer and the feet look smaller (Kouchi, 2000). Several high heel design approaches have inspired ideas such as using new materials, new insoles or interchangeable heels to avoid pain in the ball of foot. For example, Thesis Couture, Inc. designed high heels made from a ballistic-grade polymer and thermoplastic polyurethane (TPU), which redistributes the body weight so that 50 percent of the body weight is put on the ball of the foot, while the other 50 percent is put on the heel portion. However, this kind of impact pain can be lessened (Thesis Couture, 2015). Raphael Young, Inc. utilized the flexible rubber and latex gel injections in the leather soles to reduce the pain on the balls of the feet (Raphael Young, 2011). Also, Dr. Scholl's® developed DreamWalk® High Heel Insoles to help relieve foot pain when wearing high heels (Dr. Scholl's, 2009). These design approaches may help reducing foot pain temporarily. However, such products are limited in their intended use through the requirement of an insertion insole for each shoe that a user wants to wear. For example, Dr. Scholl's® products and flexible rubber may work for a long time, but the material may limit the overall functionality. Also, it might be inconvenient for users to change shoes because they always need to switch Dr. Scholl's® insoles from their current used shoes to the shoes they want to wear. Therefore, an alternative design solution is needed.

1.3 Goal and significance of the study

The higher the height of the heel of a dress shoe, the more uncomfortable the dress shoe is (Hong et al., 2005; Kouchi, 2013). The reviews of the literature related to the effects of wearing high heels on health, and the comfort level of wearing high heels, are used to identify that high-heel shoes increase the weight bearing on the fore-foot region and relieves the load on the heel region. This is why high-heeled shoes cause so much pain to the ball of the foot. Therefore, a more uniform weight distribution over a larger contact area, reducing concentration of weight bearing on the forefoot, and increasing it on the heel in high-heeled shoes, can improve foot comfort. Also, adjusting the heel height can be a good solution since lower heel height can increase the load on the heel and decrease the load on the forefoot.

The goal of this study is to investigate and evaluate effective design strategies to minimize foot pain resulting from wearing high-heeled shoes. The following are the specific objectives of this research effort:

1. Developing an automatic heel height adjustment system, which can help relieve foot pain by changing the state of the shoe according to the wearer's needs.

2. Developing an automatically rotating outsole in order to adjust the pressure between forefoot and heel portion.

3. Developing a testing shoe system, which could customize the shoes according to the shape and size of every individual foot.

4. Exploring the possibility of using soft robotics system to build adjustable arch support for women's feet.

Based on the aforementioned research objectives, this study carries out a design project and biomechanical evaluation: Phase I development of prototypes of a smart high heel system with automatic angle adjustment system, and Phase II evaluation of the effectiveness of the prototypes on improving foot comfort.

1.4 Hypothesis

This research presents four hypotheses about the proposed design solution to address the problems of the existing high-heeled shoes:

Hypothesis 1: The adjustable heel height system will relieve pain on the ball of the foot by adjusting the load between the forefoot and the heel.

Hypothesis 2: The automatically rotating outsole will prevent pain on the ball of the foot by redistributing the load from the wearer's forefoot to their mid-foot and heel.

Hypothesis 3: Increasing foot contact area will reduce peak plantar pressure by providing more support to the feet.

Hypothesis 4: The new design will improve foot-comfort by reducing peak plantar pressure and redistributing plantar pressure in the high heel.

CHAPTER 2

LITERATURE REVIEW

2.1 Effects of wearing high heels on health

High-heeled shoes create deign challenges with regard to the comfort of women's feet. Previous studies have focused on the correlations between the physical measurements of the subjects and the increased heel height, as well as problems caused by high heels. This chapter identifies which studies have been done and provides background information for the methodology of designing and examining high heels.

2.1.1 Negative impacts of wearing high heels on weight distribution

The elevation of heel height contributes to an increase of plantar pressure applied to the forefoot region of high-heeled shoe wearers, creating the negative effect of wearing high-heeled shoes with respect to weight distribution in the foot region. A number of researchers have performed experiments to understand the plantar pressure difference of those who wear high-heeled shoes of increased heel height. The weight distribution, while wearing three different heights of dress shoes (1.91, 3.81, 7.62cm), was measured by Snow and Williams (1994). Their approach showed that the overall pressure applied to the forefoot region was increased during a standing task in proportion to the elevated heel height. Broch et al. (2004) presented a graphical approach to illustrate the effect of the increased heel height of a shoe on the weight under different foot regions. Through their calculation of the change in the distribution of plantar pressure, they demonstrated that the forefoot pressure was elevated and the pressure at the heel region was decreased corresponding to the increased heel height. Eisenhardt et al. (1996) measured foot pressure wearing high heels during a walking task and reported the increase of the medial forefoot pressure with progressively higher heels. The work described above relies on the foot pressure measurement to define the effect of the change of heel height on weight distribution. Without pressure measurement, but using the calculation of the foot contact area, Nyska et al. (1996) demonstrated that wearing high heels causes the contact area at the mid-foot region to be reduced.

2.1.2 Negative impacts of wearing high heels on foot morphology

Wearing high-heel shoes has the deleterious effect on female wearer's feet by introducing serious foot problems and changing foot morphology. Early in the 1850s, Watson (1857) had already found that women wearing high heels suffered from foot problems like corns and crumpled toes as a result of high plantar pressure tolerated by the ball of the foot. Humphry (1861) reported that not allowing sufficient space for the toes was the main reason for cramping from the toes being driven forward. In 1868, the editors (1868) from Harper's Bazaar suggested that the deformity of the foot, when wearing high heels, was the result of wearing abnormally narrow high heels. Jackson (1874) reported that the elevation of heel height put more load on the toes, eventually introducing the problem like bunions and corns to wearer's feet. The Ladies Home Journal (1908) showed that high-heeled shoes forced the foot bone to form an abnormal shape. This study was conducted using X-ray photographs on the foot after low and high-heeled shoes were worn. Further research (1922) also found that high heels forced the foot bones into unnatural positions, where the toes were squeezed, resulting in the deformity of the foot. Daily mail (2013) reported that wearing high heel is the leading cause of women's foot and leg problems such as ball of foot pain, hammer toes, bunions, ankle injury, and tightness of the Achilles tendon and calf (Fig 2.1).

Kouchi et al. (2000) reported that the increase of the heel height caused the length of the medial and lateral arch lengths and the breadth of the foot to shorten. Furthermore, they found that sections 1-8 of the foot became higher, narrower and rounder, as illustrated in Figure 2.2. Schwartz and Heath (1959) suggested that the amount of shortening of the heel-to-ball length of the whole foot was correlated with the increase of the curvature of the shoe shank. Furthermore, they demonstrated that wearing higher heels caused the foot to slide forward in the shoes, as shown in Figure 2.3. The sliding forward of the foot generated the health issue like the risk of hurting the toes, inadequate support for mid-foot, and incorrect fit at the heel for high heel wearers.

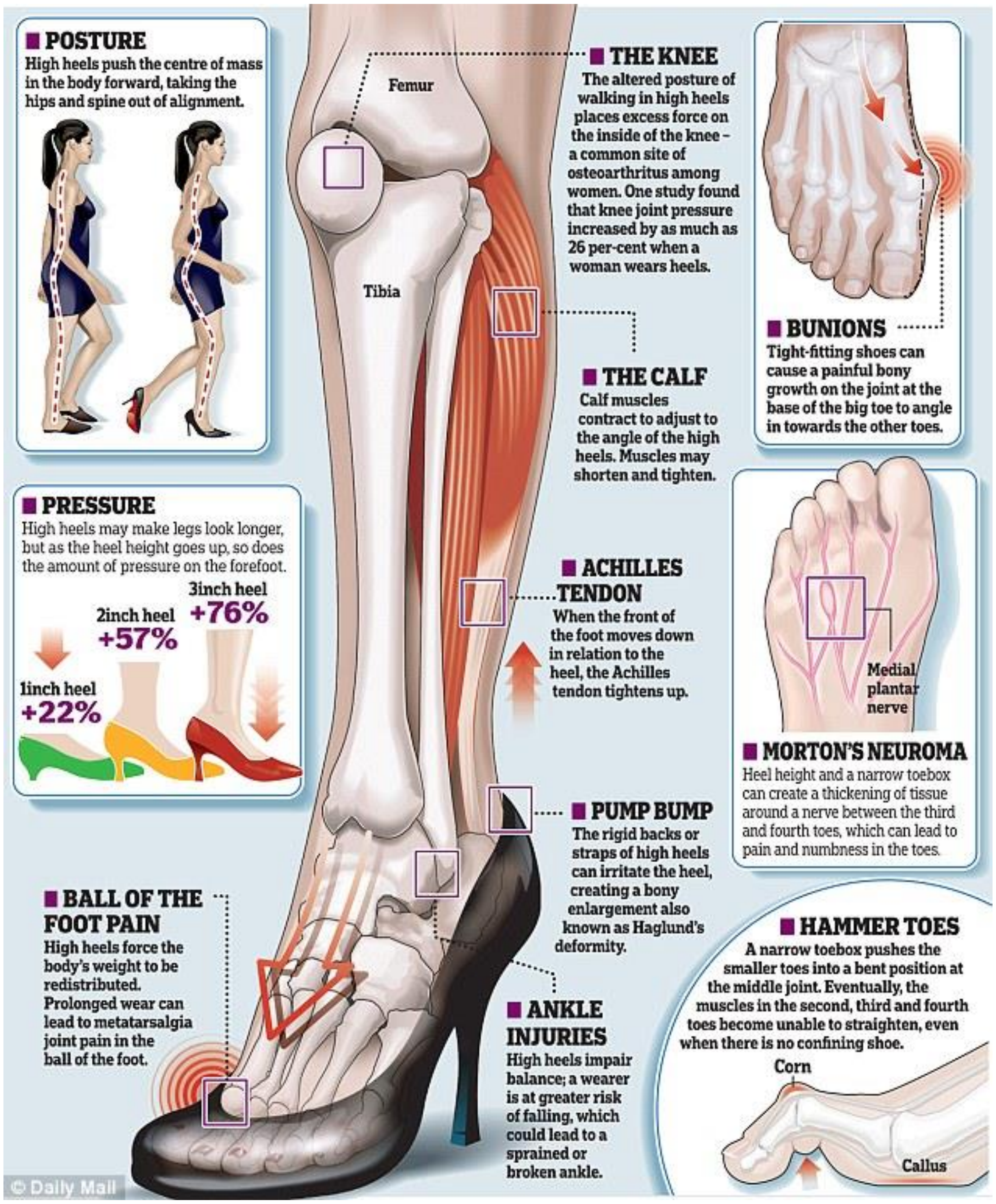
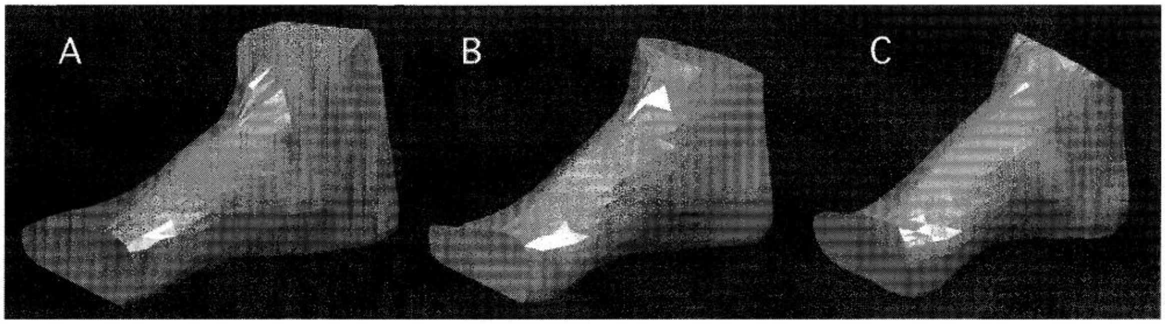
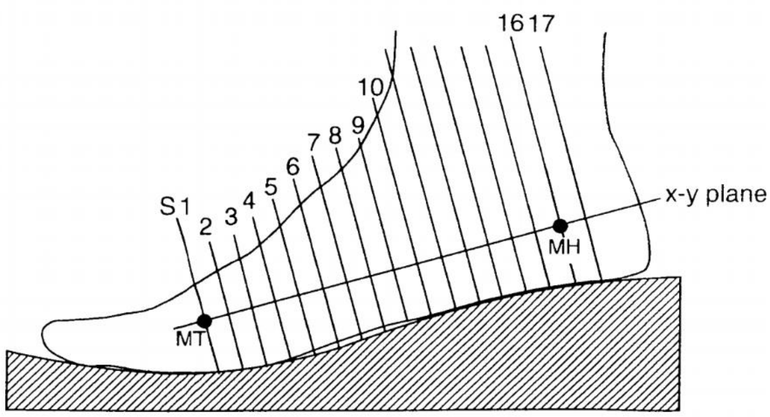


Figure 2.1: How Female Feet Suffer for High Heels. Retrieved July 13, 2013 from http://www.dailymail.co.uk/femail/article-2381290/Ouch-Thats-killer-heels-Revealed-suffer-painful-feet.html. Copyright 2016 by Daily Mail.



a) Example of Measured 3D Form. A: Heel Height 0 cm. B: Heel Height 4 cm. C: Heel Height 8 cm.



b) Cross Section Calculated on the Foot. MH Medial Heel Points; MT Metatarsal Tibiale.

Figure 2.2: Foot Morphology. Adapted from "3D foot shape and shoe heel height," by M. Kouchi and E. Tsutsumi, 2000, Anthropological Science, 108(4): 331–343. Copyright 2000 by the Anthropological Society of Nippon.

2.1.3 Posture and mobility

Wearing high-heeled shoes causes demonstrable changes in walking patterns by reducing range motion of the knee, walking velocity and stride length. It also brings

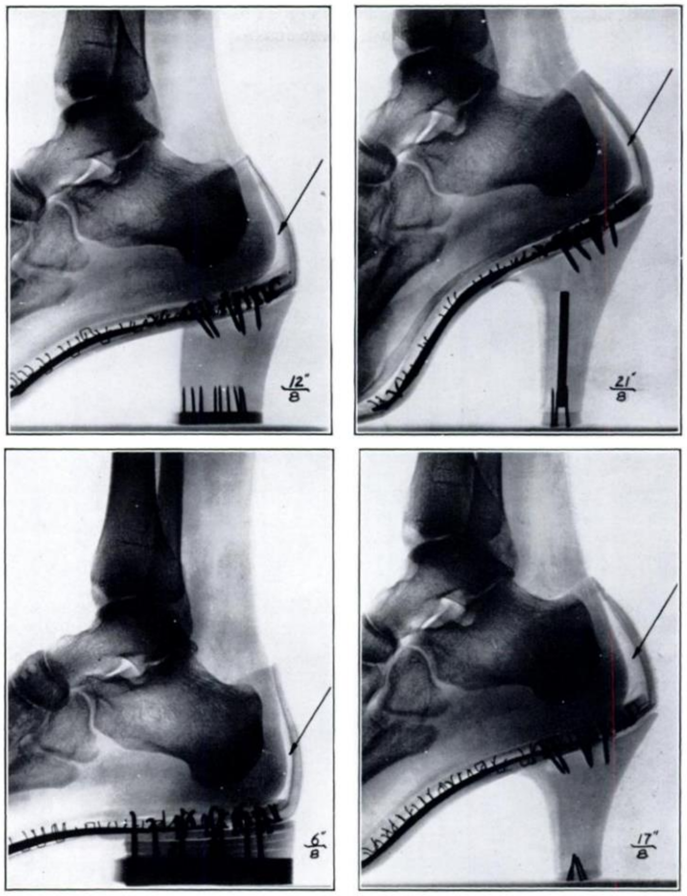


Figure 2.3: Example of the Sliding Forward of the Foot in the Shoe Accompanying Elevation of the Heel. Adapted from, “Preliminary findings from a roentgenographic study of the influence of heel height and empirical shank curvature on osteo-articular relationships of the normal female foot.” (B.P. Schwartz and A.L. Heath, 1959, Journal of Bone and Joint Surgery, 46-A: 1065–1076), Copyright 2016 by the Journal of Bone and Joint Surgery, Inc.

negative impact to female wearers such as increasing muscle fatigue significantly by increasing oxygen consumption. Merrifield (1971) found that the step length and stride length of those who wear high heels with height from 2.5 to 3 inches were decreased. The high-heeled shoe wearers were forced to adjust their gait behavior by taking shorter steps. By using gait video recordings, Gehlsen (1986) found that the step length of the subjects wearing high heels was significantly reduced compared to that when barefoot or wearing running shoes (see Table 2.1). Murray (1970) used sensing technology to analyze the gait of the subjects wearing high heels and found that the walking velocity of each subject was reduced by 10%. The researchers (1964) also found that the knee extension of a high heel wearer was reduced by 5 degrees during a walking task. This was studied by strapping a potentiometer on the subject's knee to measure the change of angle. Ebbeling and his colleagues (1994) gave a detailed description of the increase of the time to maximum calcaneal eversion and the reduction of the time to maximum knee flexion while the heel height is elevated, as illustrated in Figure 2.4. Snow and Williams (1994) showed that the angle of supination was increased at each foot strike and the angle of maximum pronation was decreased with higher heel height by using high-speed video analysis. They also found that the plantar flexion was increased significantly by measuring ankle angles during the gait cycle. Meanwhile, the knee extension velocity was reduced while heel height was elevated. Philips and his colleagues (1991) demonstrated that high-heeled shoes relocated the position of women's heels and changed the angle of pronation of the foot during walking.

	Total time (sec)	Stance time (sec)	Swing time (sec)	Step length (cm)	Line of gravity distance of toe (m)
Barefoot					
X	1.004 [a]	0.646 [a]	0.358 [b]	0.569 [b]	0.040 [b]
SD	0.057	0.035	0.026	0.028	0.006
Running shoes					
X	1.056 [b]	0.692 [b]	0.358 [b]	0.572 [,b]	0.040 [b]
SD	0.069	0.056	0.022	0.041	0.003
High heeled					
X	0.987	0.644	0.343	0.553	0.036
SD	0.049	0.041	0.018	0.031	0.005

[a] Significantly different from running shoes;
[b] significantly different from high heeled shoes.

Table 2.1: Mean and Standard Deviation Values for Gait Characteristics. Adapted from "Effects of heel height on knee rotation and gait," by G. Gehlsen, J. S. Braatz, and N. Assmann, 1986, Human Movement Science, 5(2):149–155. Copyright 2016 by ScienceDirect.

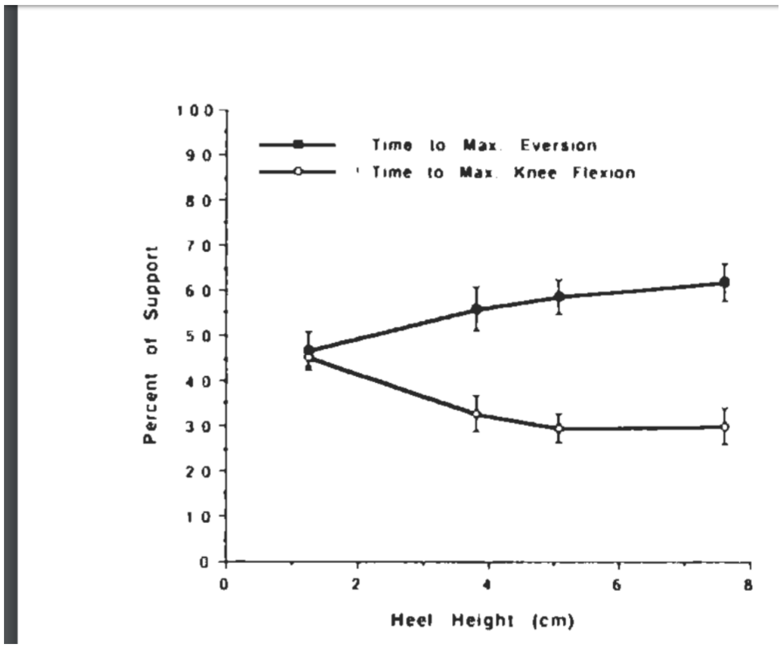


Figure 2.4: Percent Times to Maximum Knee Flexion and Maximum Calcaneal Eversion as a Function of Heel Height. Adapted from “Lower extremity mechanics and energy cost of walking in high-heeled shoes,” by C.J. Ebbeling, J. Hamill, and J.A. Crussemeyer, 1994, Journal of Orthopaedic and Sports Physical Therapy, 19(4): 190–196. Copyright 2016 by Journal of Orthopaedic and Sports Physical Therapy.

Joseph and Nightingale (1956) described the effect of high heels on soleus muscle using electromyography (EMG). They reported that the activity of the subject’s soleus muscle was increased significantly during standing task. As shown in Figure 2.5. Mathews and Wooten (1963) reported the energy consumption of subjects, wearing a 3-inch heel, increased 12 percent when compared to the same subjects wearing low-heeled shoes by analyzing their oxygen consumption. Esenyel and his colleagues (2003) reported the work performed by ankle plantar flexor muscle was decreased during the stance phase. They also demonstrated that the work performed by the hip flexor muscles was increased when the task was transformed from stance to swing.

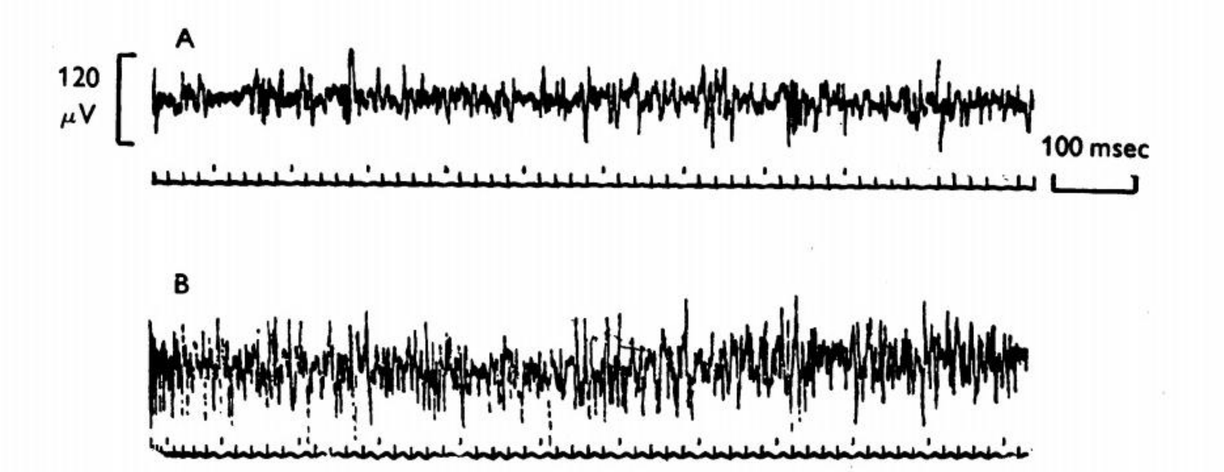


Figure 2.5: A) the Recordings from Soleus, Standing at Ease with Low Heels. B) the Recording from Soleus, Standing at Ease with High Heels. Adapted from “Electromyography of muscles of posture: Leg and thigh muscles in women, including the effects of high heels.” by J. Joseph, and A. Nightingale, 1956, J. Physiol. 132:465-468. Copyright 1956 by the Journal of physiology.

2.2 Negative impacts of wearing high heels on comfort

Wearing high heels for a long time brings a significantly negative effect on foot comfort, especially in the forefoot region. Lee and Hong (2005) demonstrated that higher heel height increases the pressure at the forefoot region and decreases the foot discomfort rating as compared to low heeled shoes during a walking task (Fig 2.6). De Castro and his colleagues (2009) showed that wearing high heels not only caused foot pain, but also increased the circumferences of women’s metatarsal heads. Lord and Bashford (1996) showed that the participants performed worse for the walking task while they wore high heels but performed the experimental task very well when they were bare foot or wore low-heeled shoes.

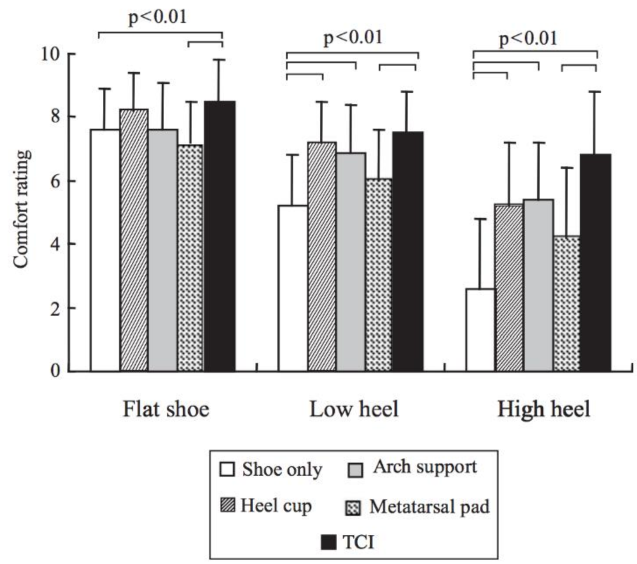


Figure 2.6: Comparison of the Comfort Rating for Each Test Condition. TCI: Total Contact Insert. Adapted from "Effects of shoe inserts and heel height on foot pressure, impact force and perceived comfort during walking," by Y.H. Lee and W.H. Hong, 2005, Applied Ergonomics, 36: 355–362. Copyright 2004 by ScienceDirect.

2.3 Development efforts to solve issues of foot pain while wearing a high heel

2.3.1 An Interchangeable heel

High heels can include a heel height adjustment system to solve foot pain by adjusting heel height. It can include a removable heel to allow the state of the shoe to switch between, for example, a flat shoe and a high heel. This application can help relieve foot pain by changing the state of the shoe according to the wearer's needs. A number of researchers have explored this idea. Handel et al. (2012) developed an adjustable height high-heel shoe consisting of a low heel lift component, which could be fixed by a beveled edge at the top part of the heel when it needs to be converted to a high heel shoe. Colon (1994) developed a high heel component, which could be attached directly to the heel bottom portion of the flat shoe in order to transform the shoe to a high-heel state. Schupbach (2007) developed a shoe with an interchangeable heel including a sole component and a front securing component. The front securing component was used to lock the sole component to the shoe if it needs to adjust the shoe to a high heel state. Visser (2012) developed a shoe with a removable and interchangeable heel including a fastener, which could secure the removable heel to the bottom part of the shoe to elevate the heel height.

The work described above relies on a removable heel system to adjust heel height to relieve foot pain. Based on a removable heel system, Gallegos (2008) further developed an interchangeable heel including a compressible spring inside the heel to relieve foot pain by absorbing the shock caused by heel strike. Also, Anderson (2014) extended the work described above by building a removable heel system including a resilient stem holder, configured to cushion the foot and reduce shock.

Figure 2.7: Thesis Couture High Heel. Retrieved May 12, 2016 from http://thesiscouture.com/. Copyright 2016 by Thesis Couture.

2.3.2 The effects of new materials applied to the high heel

No discussion of designing a comfortable high-heeled shoe is complete without considering the possibility of utilizing the innovative material of the shoes. There has been some research on replacing the traditional material of a high heel with new material for the production of better foot comfort. For example, a material like silicon rubber can be used on the shoes to provide cushioning and absorb shock from the foot strike while walking. The application of using new materials is attractive because the innovative material could provide better shock absorption to relieve foot discomfort. Thesis Couture (2015) was trying to adjust the distribution of loading at the ball of the foot region from 70 percent to 50 percent by integrating ballistic-grade polymer, thermoplastic polyurethane (TPU) and aerospace-grade foam in the high-heeled shoes to cushion the foot (Fig 2.7).

Unlike the method Thesis Couture used here, Raphael Young (2011) put the flexible rubber and latex gel injections in the leather soles to reduce the pain at the balls of the feet (Fig 2.8).

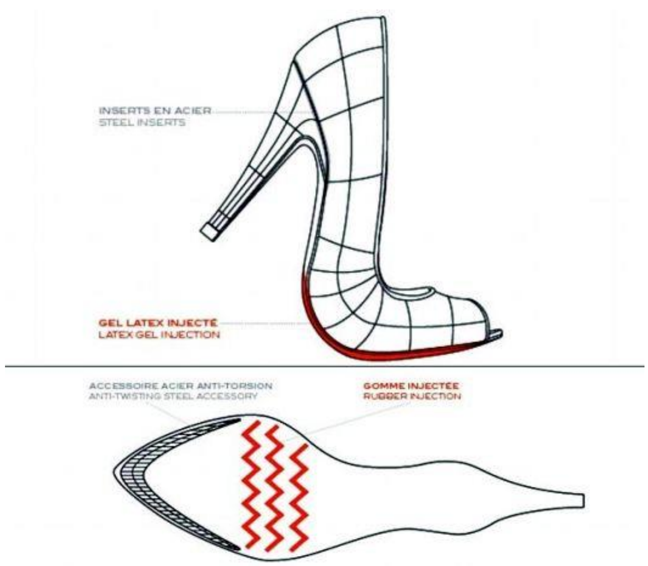


Figure 2.8: Raphael Young High Heel. Retrieved May 12, 2016 from http://www.raphaelyoung.com/. Copyright 2016 by Raphael Young.

High-heel insoles have been developed to help prevent foot pain from heels. Dr. Scholl's® (2009) showed substantial benefits from utilizing insole in high-heeled shoes. They claimed that their products could help prevent foot pain from wearing high heels (Fig 2.9). Insole support systems developed by Singleton (2010) contained a mid-foot support using compressible cushioning material, providing enough support to the mid-foot region of the wearer's foot to redistribute the load from the wearer's forefoot to her mid-foot.

Figure 2.9: Dr.Scholl’s DreamWalk. Retrieved May12, 2016 from https://www.drscholls.com. Copyright 2016 by Dr.Scholl’s.

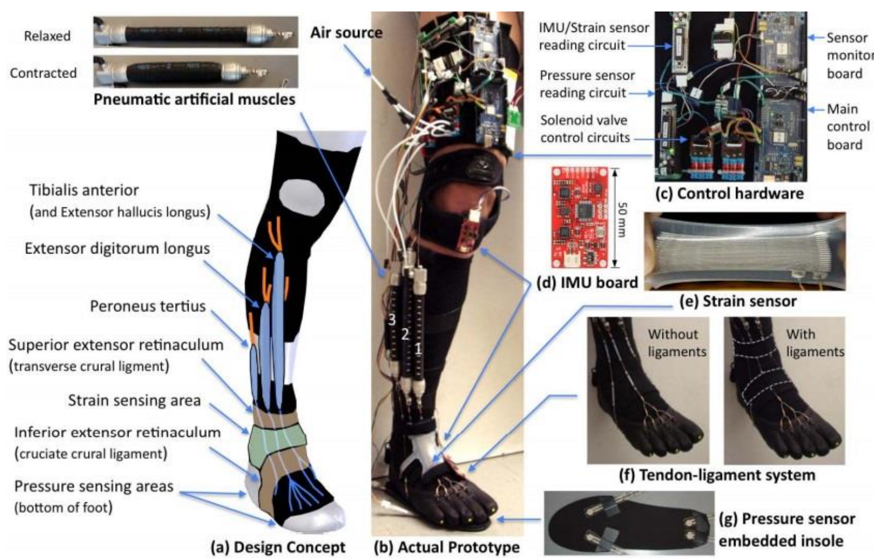
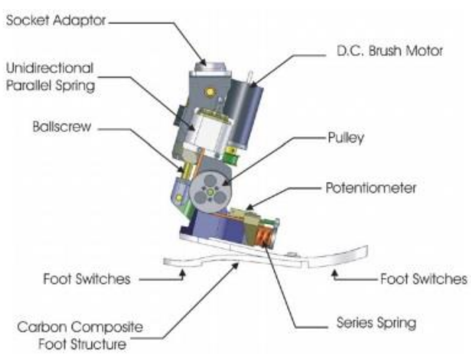


Figure 2.10: Main Design of the Active Soft Orthotic Device, Highlighting Key Components. Adapted from “Bio-Inspired Active Soft Orthotic Device for Ankle Foot Pathologies,” by Y. Park, B. Chen, D. Young, L. Stirling, R. J. Wood, E. Goldfield, and R. Nagpal, 2011, Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'11), 4488-4495. Copyright 2016 by Journal of Orthopaedic and Sports Physical Therapy.

2.4 Wearable technology as a potential design solution

Wearable technology is likely to provide a solution to high-heel shoes. Wearable technology can benefit users by offering enhanced functionality and improved comfort by incorporating small responsive electronics into a wearable interface - fastened on the body (e.g., clothing, shoes, and accessories). For example, some researchers combined a prosthesis and/or exoskeleton with electronic components to help people perform better during a walking task. Park et al. (2011) used the pneumatic artificial muscles to develop a soft ankle foot orthotic device, which could be used to treat the patients who suffered gait pathologies. Several sensors and electronic components, e.g. a microcontroller, were utilized on a device they designed for implementing gait training and analyzing gait pattern (Fig 2.10).



(a) Side View. (b) Physical Prototype.

Figure 2.11. Mechanical Design of the Prosthesis. Both (a) and (b) are adapted from "Powered ankle-foot prosthesis improves walking metabolic economy," by S. K. Au, J. Weber, and H. Herr, 2009, IEEE Trans. Robot., vol. 25, no. 1, pp. 51–66, Feb. Copyright 2016 by IEEE.

Herr and his colleagues (2009) developed a powered prosthesis consisting of various force-controllable actuators, DC motors and switches. Compared to the traditional prostheses that exist on the market, the powered prosthesis reduced the amputee's metabolic rate by 14% (Fig 2.11).

Pratt et al. (2004) developed a knee device by using an array of elastic actuators. Such a device may assist the users to climb stairs and perform knee bends while they carry a significant load on the body. Asbeck and his colleagues (2014) developed a fully autonomous soft exo-suit providing the assistance to the wearer's ankle and hip when performing a walking task. The result showed that the metabolic rate of the subject, powered by their suit, is reduced by 6.4% as compared to the same subject unpowered by the suit during a walking task. Vukobratovid (1990) also created an exoskeleton, for the purpose of helping a patient walk, by requiring the exoskeleton to detect pre-defined trajectories. Polygerinos and his colleagues (2015) developed a soft robotic glove to strengthen hand rehabilitation for people having problems with functional grasp pathologies. The glove was mechanically programmed by the software to reach the desired range of motion of the fingers for the patients (Fig 2.12).

Figure 2.12: The Prototyped Soft And Lightweight Robotic Hand Assistive Device. Adapted from "Lower extremity mechanics and energy cost of walking in high-heeled shoes," by P. Polygerinos, Z. Wang, K.C. Galloway, R.J. Wood, C.J. Walsh, 2015, Soft Robotic Glove for Combined Assistance and at-Home Rehabilitation. Robotics and Autonomous Systems (RAS) Special Issue on Wearable Robotics. 73 :135-143. Copyright 2016 by Robotics and Autonomous Systems (RAS).

CHAPTER 3

METHODOLOGY

3.1 Electro-mechanical design of the high heel

The core design idea to improve foot comfort while wearing a high-heeled dress shoe is to transfer the part of the plantar pressure from the forefoot region to the mid-foot and heel region. This weight balance, over the larger contact area, will minimize the force concentration and peak plantar pressure. Meanwhile, it also needs to provide more support at mid-foot and heel region. Based on these two main ideas, the proposed high-heel design was developed using an automatic angle adjustment system and a heel height adjustment system, minimizing pain in the ball of foot.

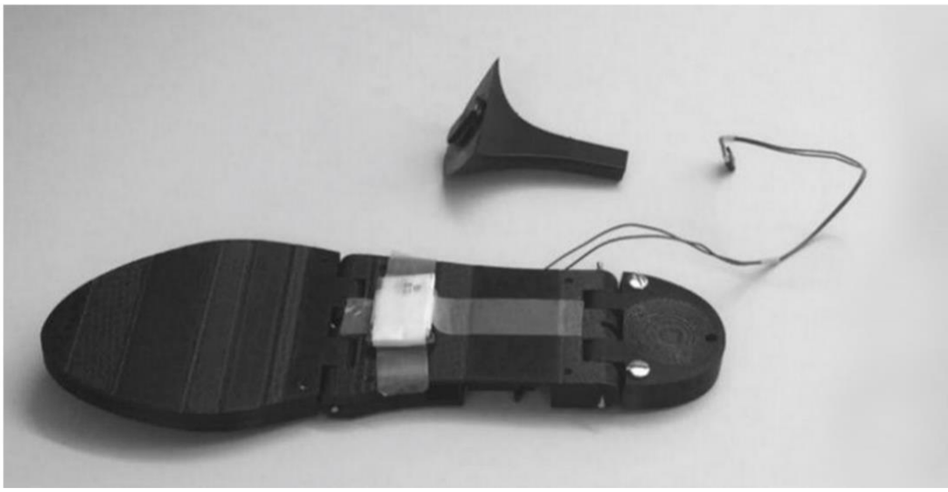
3.1.1 Functional requirements

1) Automatic angle adjustment system

The proposed shoe has an automatic angle adjustment system in the modular design structure. This allows the shoe to allow the state of the shoe to automatically switch between a flat shoe and a high-heel within seconds. Embodiments of the application could help relieve foot pain by changing the state of the shoe based on the wearer's needs. The automatic angle adjustment system includes a rotatable outsole. For example, the forefoot and the heel portions of the outsole may rotate relative to the other outsole portions. A pressure sensor is used to signal a change in the state of the shoe. The pressure sensor is located on the shoe such that the state of the outsole can be changed in response to signals from the sensor. The outsole state response time is on the order of seconds, or as little as one second or less.

2) Automatic heel height adjustment

The interchangeable design allows for quick adjustment of the height of the heel, as shown in Figure 3.1. The developed high-heeled shoe consists of an internal battery that is charged by a standard connection port, a USB charging device to charge the internal battery using electronic devices such as a laptop or other portable computer appliance, and the interchangeable heel, which allows the wearer to adjust her shoe between a high-heel shoe or a flat shoe state depending on her preference or need.



a) Side View of the Developed Shoe Showing the Heel Detached from The Outsole

b) Side View of the Developed Shoe Showing the Heel Attached to The Outsole.

Figure 3.1: Convertible High Heel.

The shoes described herein include the following components: (1) two motors, including corresponding driveshafts; (2) a driveshaft including a plurality of gears (*e.g.*, seven gears); (3) a driveshaft configured to adjust a rear sole section (heel) and a front sole portion (forefoot); (4) a microcontroller connected to one motor, one pressure sensor, one battery and one USB charger; and (5) a sole, including a plurality of cavities (*e.g.*, six cavities). In one particular example, the first cavity can be used to house a motor; the second cavity can be used to house a front part of the drive shaft; the third cavity can be used to house the battery; the fourth cavity can be used to house the microcontroller; the fifth cavity can be used to house the USB charger; and the sixth cavity can be used to house a rear part of the driveshaft.

The present shoe was embodied as an adjustable shoe having an outsole. The outsole has a middle portion, which is hinged to a forefoot portion at a forefoot angle. The middle portion of the outsole was also attached to a heel portion at a heel angle. Figure 3.1A depicts the outsole configured in a low-heel state (*i.e.* a flat shoe configuration). Figure 3.1B depicts the outsole configured in a high-heel state.

The heel was configured to have any height. For example, the heel may be configured as a high heel, such as that depicted in Figures 3.1A. In another embodiment, the heel may be configured as a low heel such as that depicted in Figures 3.1B. The heel is also comprised of a coupler which is configured to be attached to a mating coupler of the heel portion on the outsole. For example, the high heel being attached to the heel portion by way of couplers and mating couplers. The same mating couplers of the heel are attached to a corresponding coupler of the low heel and the high heel.

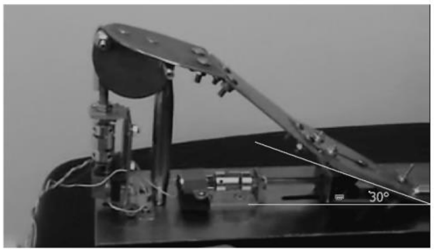
Figure 3.2: The Bottom View of the Convertible High Heel.

The shoe has multi-functional elements to support the required automatic heel height adjustment system, which include A, B, and C.

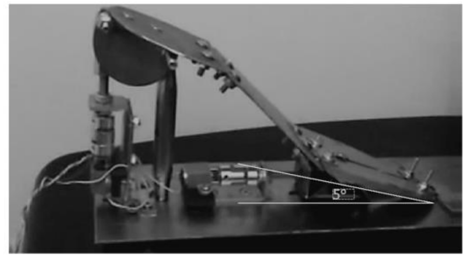
A. This spans from the forefoot portion, through the middle portion, and to the heel portion.

B. This is configured such that rotation of the front segment of the driveshaft causes the forefoot portion of the outsole to rotate about the hinge axis. As depicted in Figures 3.3A-B, the forefoot angle is changed, *i.e.* the angle of the forefoot portion is changed relative to the middle portion.

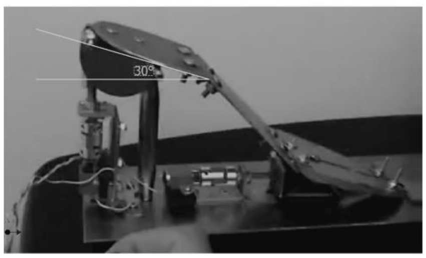
C. This is configured such that rotation of the rear segment of the driveshaft causes the heel portion of the outsole to rotate about the hinge axis. As depicted in Figures 3.3C-D, the heel angle was changed, *i.e.* the angle of the heel portion was changed relative to the middle portion.



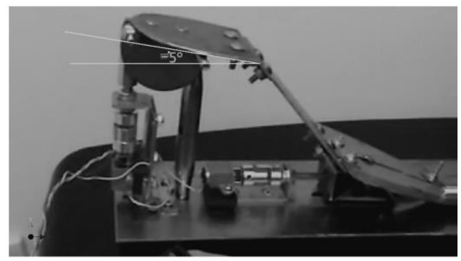
a) The View of the Prototype Shoe Showing A 30° Angle of the Forefoot Portion Relative To The Horizontal;



b) The View of the Prototype Shoe Showing A 5° Angle of the Forefoot Portion Relative to the Horizontal;



c) the View of the Prototype Shoe Showing a 30° Angle of the Heel Portion Relative to the Horizontal;



d) The View of the Prototype Shoe Showing a 5° Angle of the Heel Portion Relative to the Horizontal;

Figure 3.3: Automatically Rotating Outsole System.

The adjustable shoe further comprises the first sensor configuration to measure a force applied to an area of the outsole. For example, the first sensor is located in the heel portion of the outsole and configured to measure a force applied to the heel portion. Such an applied force is caused by the weight of the wearer. The first sensor is in communication with the processor. In this way, the first sensor provides a signal to the processor indicating the measured force, and the processor responds accordingly. For example, if the measured force exceeds a pre-determined threshold, the processor may adjust the forefoot angle and the heel angle to decrease the force measured by the first sensor.

Similarly, additional sensors measure forces applied to other portions of the outsole. For example, a second sensor was located in the forefoot portion of the outsole and configured to measure a force applied to at least a portion of the forefoot portion. In this way, the forces measured by the first and second sensors (and any additional sensors) were used to determine a distribution of the forces, *i.e.* the distribution of the wearer's weight across the outsole.

3.2 Soft Robotic Systems for High-Heeled Footwear

3.2.1 Fluidic control board structure

The purpose of building the control board is to use it to control and test the dynamic arch system to understand how the height of the arch influences the pressure distribution of the feet. The soft robotics system for the high-heeled footwear, in this study, is based on a soft robotics toolkit developed at Harvard University (Wang et al., 2014). The control board consists of: 1) a miniature diaphragm pump; 2) a solenoid valve; 3) pressure sensors; 4) a microcontroller (Arduino Mega); 5) switches and MOSFETs; 6) rotary potentiometers; 7) a breadboard; 8) power jacks; 9) various connectors, fixtures, and tubing (Figure 3.4).

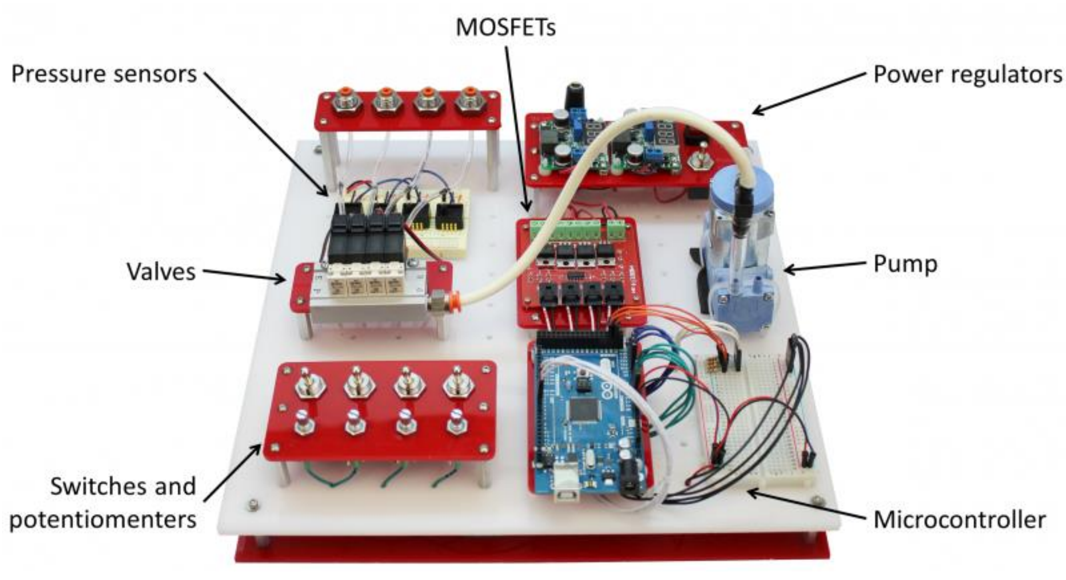
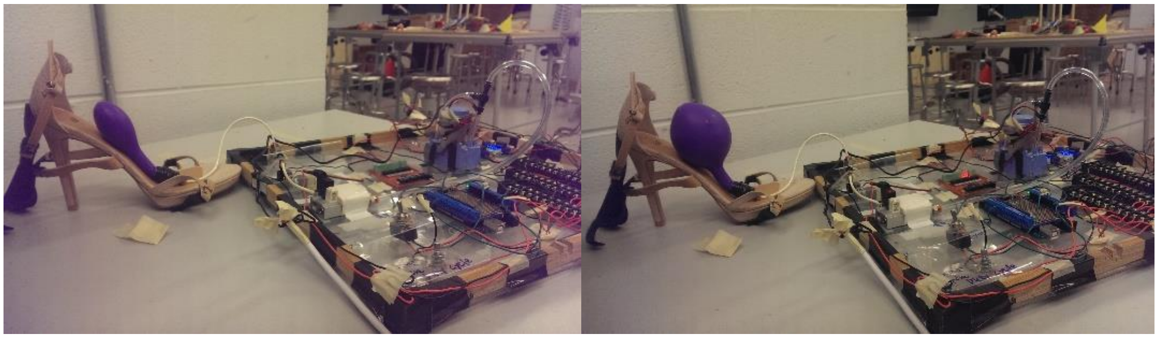


Figure 3.4: the Overview of the Control Board of the Soft Robotics System (Wang et al., 2014).

The control board uses a pump and a solenoid valve to provide air pressure inside the air chamber of the soft robotics. The system uses Pulse-Width Modulation (PWM) to regulate the timing of the opening and closing of the solenoid valves. By adjusting the PWM duty cycle the output pressure to the air chamber was adjusted. Therefore, the height of the arch could be adjusted.



a) the Soft Robotics System For a High Heel Without Air Pressure Inside The Balloon Chamber;

b) A Soft Robotics System For High Heel With Air Pressure Inside The Balloon Chamber.

Figure 3.5: A Soft Robotics System for a High Heel Arch: A) The Soft Robotics System for a High Heel Without Air Pressure Inside the Balloon Chamber; B) A Soft Robotics System for a High Heel with Air Pressure Inside the Balloon Chamber.

a) A soft robotics system for a high Heel Without Air Pressure Inside the Balloon Chamber;

b) A Soft Robotics System for a High Heel With Air Pressure Inside the Balloon Chamber.

Figure 3.6: A Soft Robotics System for High Heel Sole.

3.2.2 Using the control board

By using the potentiometer to vary the pressure and open and close the valves, it is possible to change the shape of the soft robotics. It means that the height of the arch of the sole can be adjusted, thus the height of the arch can influence the pressure distribution of the feet to be detected. While future work will enable an air chamber as part of the soft robotics system, this thesis will utilize a balloon replacement for the air chamber to highlight the effectiveness of adjusting the heel height, as shown in Figure 3.5. However, it is important to note the potential for soft robotics in this application (see Figure 3.6).

3.3 Controller Implementation

The shoe was controlled by reading and analyzing the sensor values into a microcontroller, which was mounted on the shoe. Using the sensor values and actuation system, the device automatically rotates the system and the interchangeable heel. This section outlines the control strategies of the shoe based on the electronics hardware used.

The automatic rotation mechanism for automatically rotating the outsole is controlled via a microcontroller. The microcontroller is in communication with a sensor, such as a pressure sensor. When a user activates the sensor, e.g. the pressure sensor, the automatic rotating mechanism can be configured to move the shaft according to the information received from the sensor. The movement of the shaft can cause the rotation of the rear sole section (heel) and the front sole portion (forefoot). In this manner, a flat shoe can be converted to a high heel shoe by attaching the high heel bodily to the low heel.

The present shoe may also be utilized as a method (Figure 3.7) for adjusting a shoe. This feedback system, comprising actuators, sensors, and a processor, allow the signal being measured to represent the measured force, and thus the information needed to move a portion of the outsole of the shoe. For example, the signal is received from a sensor, such as pressure sensor. Such a sensor is located at a position of the outsole to measure the force applied to at least a portion of the outsole. For example, the sensor is located in a heel portion of the outsole to measure the force applied by the weight of a wearer at the heel of a shoe.

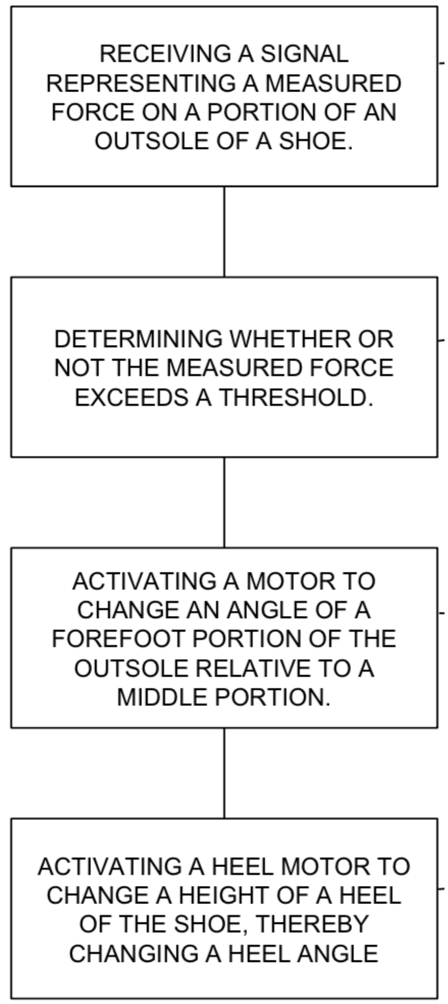


Figure 3.7: Control Strategies - The Chart Depicting the Control Strategies.

This method also includes determining whether or not the measured force exceeds a pre-determined threshold. When the measured force is determined to exceed the threshold, a motor is activated to change an angle of a forefoot portion of the outsole relative to a middle portion of the outsole. The motor may also change the angle of a heel portion of the outsole relative to the middle portion. In the embodiment, the method further comprises activating a heel motor to operate a rotary table, where the rotary table is configured to alter a heel height of the shoe. In this way, the angle of the heel portion relative to the middle portion is adjusted by changing the heel height. As such, the forefoot portion, the middle portion, and the heel portion are operable to change the state of the shoe between a high heel state and a low heel state. The low heel state may be a flat shoe state.

3.4 Evaluation

This section details the methodology of conducting the human performance experiment and explains the experimental methods for quantifying the foot comfort of the high-heel.

3.4.1 Human subjects

Thirteen female subjects (age: 27 ± (SD 7) years, shoe size: 9 ± (SD 0.5) US women) with experience wearing high heel shoes participated in this study. These subjects didn't have the problem of foot deformities (e.g., pes cavus, flat feet, club foot and hammer toe) and orthopedic issues or surgeries affecting normal gait patterns. With institutional review board approval and each participant's written consent, the data collection was performed.

Two footwear conditions were studied, including the proposed high heels (the treatment shoe), and one commercially available high heel existing on the market (the controlled shoe). Both of the heel height of the shoes is 11cm.

3.4.2 Experimental protocol

The data was collected during a set of standing and walking tasks where walking speed was adjusted by the subjects themselves. The foot comfort level was quantified by measuring the foot pressure and contact area while performing the experiment.

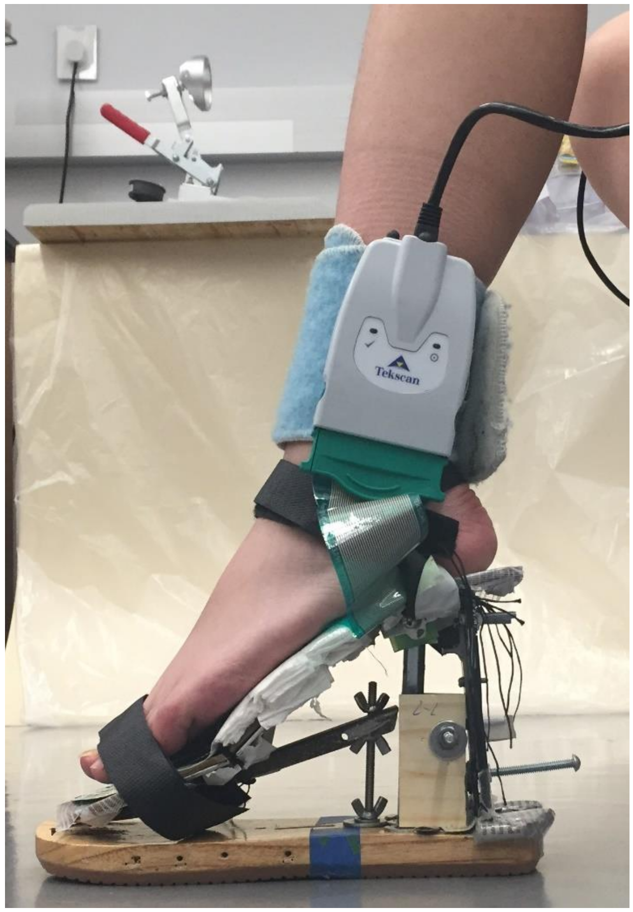
<u>*Test procedure*</u>

The order of the activities of the experiment and the description of each procedure are described below.

1. Reading and signing a consent statement.

2. Acclimating to the shoes and the flexible F-Scan® insole sensing system.
3. Testing foot pressure and contact area measurement wearing controlled and treatment shoes (Figure 3.8 and Figure 3.9).
4. Resting.

Figure 3.8: A Subject in the Experiment.



(a) the Treatment Shoe

(b) the Controlled Shoe

Figure 3.9: The Treatment Shoe.

Foot pressure and contact area

For both the controlled and treatment shoes, the plantar pressure and contact area was measured under two conditions: measurement in static condition and walking.

Foot pressure distributions and contact area were measured using the flexible F-Scan® insole sensing system (Tekscan, Inc., Boston, MA), as shown in Figure 3.8. This study used the identical pair of sensors for each subject allowing data comparisons. The calibration was completed with subjects standing on the sensor in order to check the error caused by the problem of the sensor quality.

Figure 3.10. F-Scan System. Retrieved May12, 2016 from https://www.tekscan.com/products-solutions/systems/f-scan-system?tab=add-ons. Copyright 2016 by Tekscan,Inc.

Before the recording begins, the subjects were required to practice walking for 3 minutes to minimize the issue of the temperature effects and be familiarized with the given shoes and experimental protocol. The participants walked about 10 meters at self-preferred speed. In order to prevent the effect of walking speed, the subjects were suggested to walk at their normal patterns.

For the two conditions tested, the order of recording foot pressure was randomized.

<u>Survey and interviews for rating perceived comfort levels</u>

All subjects were asked to complete a detailed questionnaire that included questions on the pain level of the forefoot, arch and heel, wearing treatment high heels compared to controlled high heels (Figure 3.11, 3.12, and 3.13). Participants' responses were recorded via written form. Approximately 20 minutes were taken for each participant to complete each interview. A total of 13 participants were interviewed.

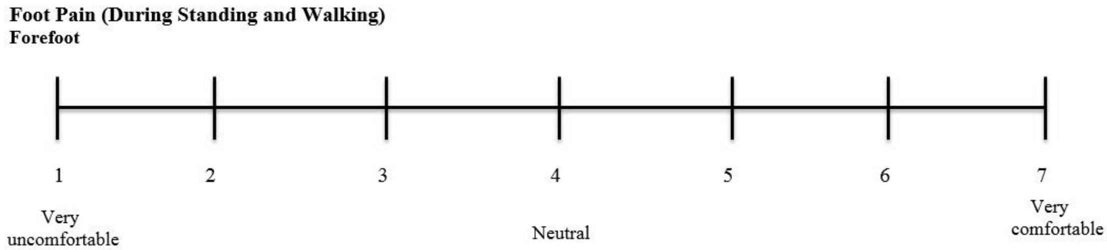


Figure 3.11 Comfort Level Table for Forefoot Region

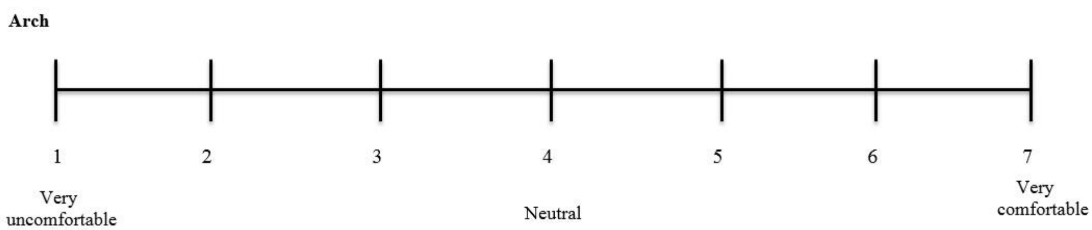


Figure 3.12 Comfort Level Table for Arch Region

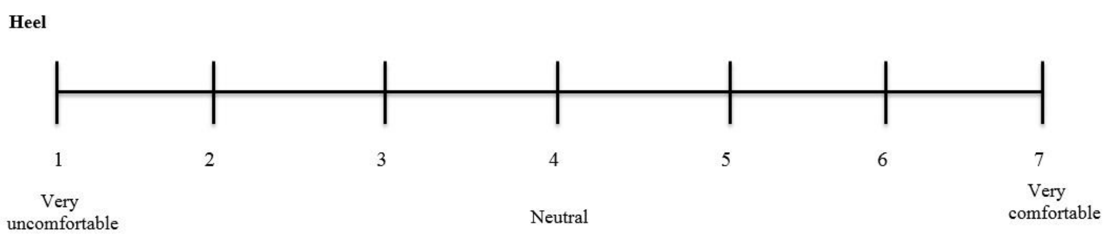


Figure 3.13 Comfort Level Table for Heel Region

The subjects were also asked to compare the treatment high heels with controlled high heels, indicating how much better the treatment high heels performed compared to the controlled high heels (Figure 3.14). Furthermore, another four questions were designed for the interview as follows:

1). Do you think the proposed design prototype could improve your foot comfort compared to the commercial available high-heeled footwear?

2). How do you like the idea of convertible shoes?

3). Would you buy some convertible dress shoes like this prototype? Why or why not?

4). Do you have any recommendation on the improvement of the developed prototype?

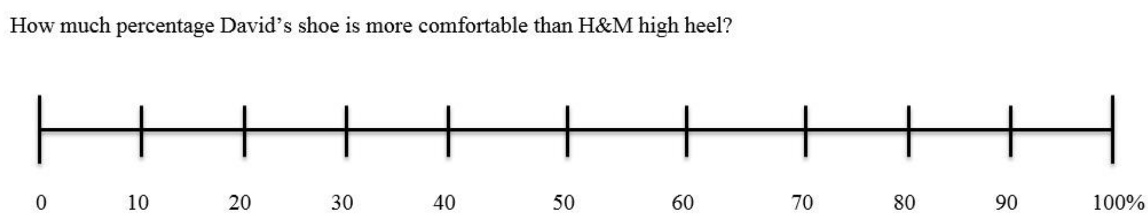


Figure 3.14: The Comparison Between the Treatment and Controlled Shoe.

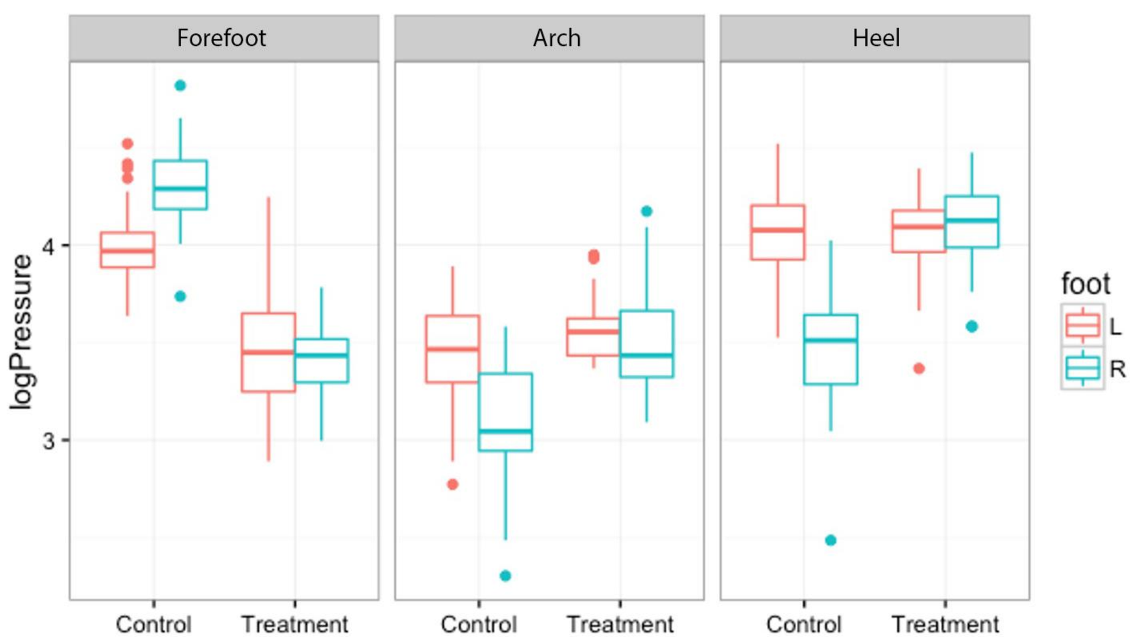
Data analysis

This study recorded the data in three regions: forefoot, arch, and heel from the control and treatment shoes.

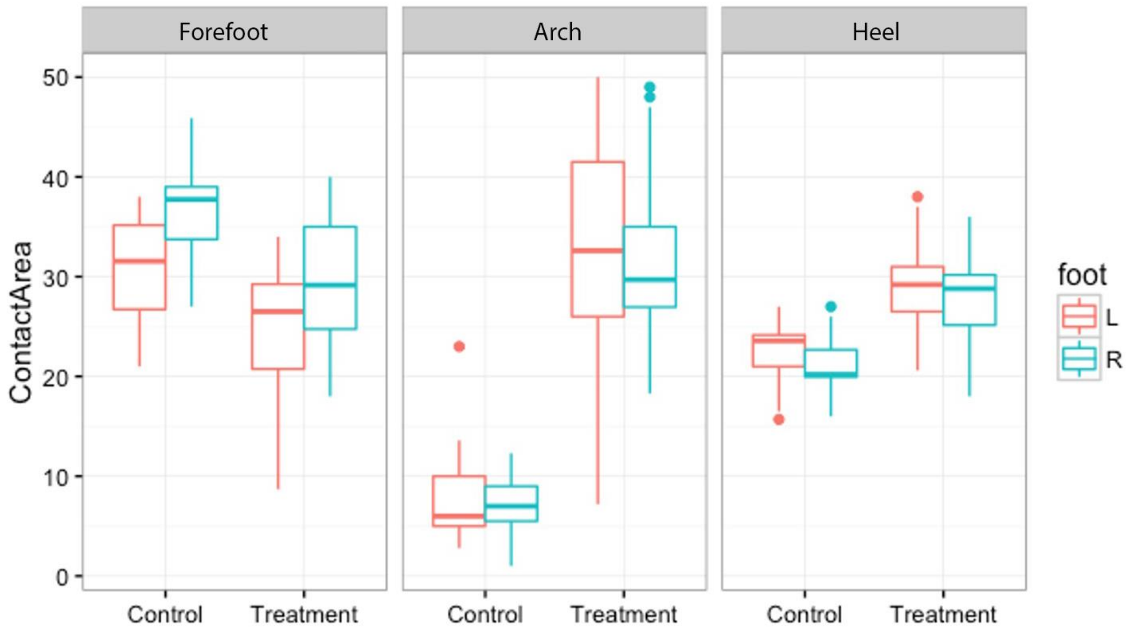
For each trial, this study recorded only the middle three steps of each leg with three repeats for each task. The recording data measured in the shoe-only condition (control shoes) used as the reference for comparing with new shaped-insole used conditions (treatment shoes).

Mixed models analysis was employed using R (version 3.3.0) to determine if the new shape of the treatment shoes have a significant effect on foot comfort (pressure and contact area) compared to the controlled shoes. The experimental design was repeated measures because each subject was measured repeatedly with 2 different shoe types for three standing and three walking trials. Four separate statistical models were proposed, namely standing-pressure, standing-contact area, walking-pressure and walking-contact area. Responses for pressure were transformed by the logarithm function. Using the logarithm transformation, the residuals are more consistent with the normal distribution. (Nachtsheim, Neter, Kutner and Wasserman, 2004)

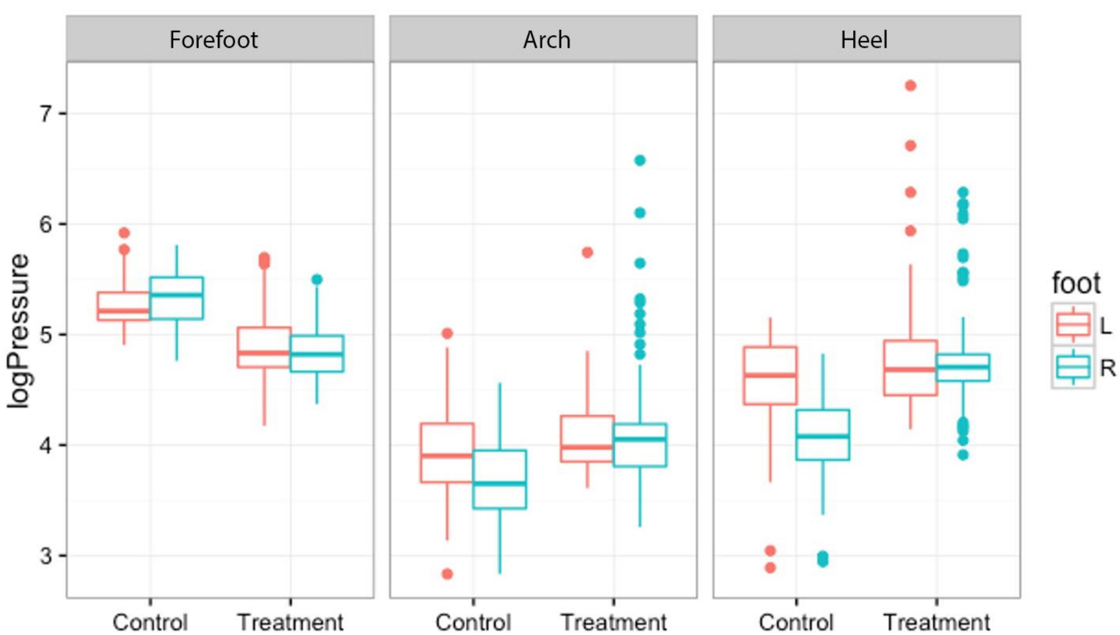
Fixed independent variables of interest are shoe type, foot regions and their interaction. The models also control for right and left feet as fixed effect since raw pressure and contact area data are different for right and left feet in both walking and standing trials of two heels used in experiment according Fig. 3.15. Therefore, the variability of the difference between two feet of one subject was taken into consideration, making the result of the plantar pressure and contact area data more precise.



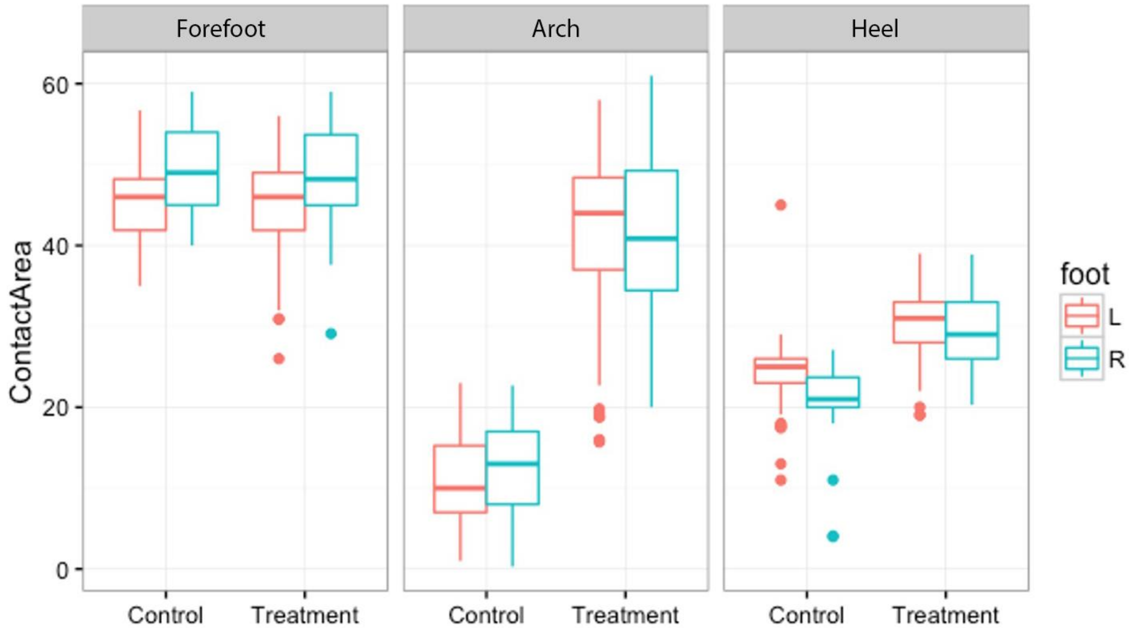
a). Foot Difference for log Pressure in Three Foot Areas of Two Heels in Standing Trials



b). Foot Difference for Contact Area in Three Foot Areas of Two Heels in Standing Trials



c). Foot Difference for log Pressure in Three Foot Areas of Two Heels in Walking Trials



d). Foot Difference for Contact Area in Three Foot Areas of Two Heels in Walking Trials

Figure 3.15: Foot Difference

Random effect in this study have a nested structure. In two models for standing trials, subject, heels nested in subjects, and replicates nested within heels and subjects, are random effects. While in two models for walking trials, subject, heels nested in subjects, and replicates nested within heels and subjects, steps nested within replicates, heels and subjects are random effects.

Linear fit equations and least-squares means (LS means for short) for these four linear models were employed to estimate and predict the difference of pressure and contact area between two shoe types in three foot areas for both standing and walking trials. Post-hoc pairwise comparisons using Bonferroni correction were conducted. All statistical tests were done at the 0.05 level of significance.

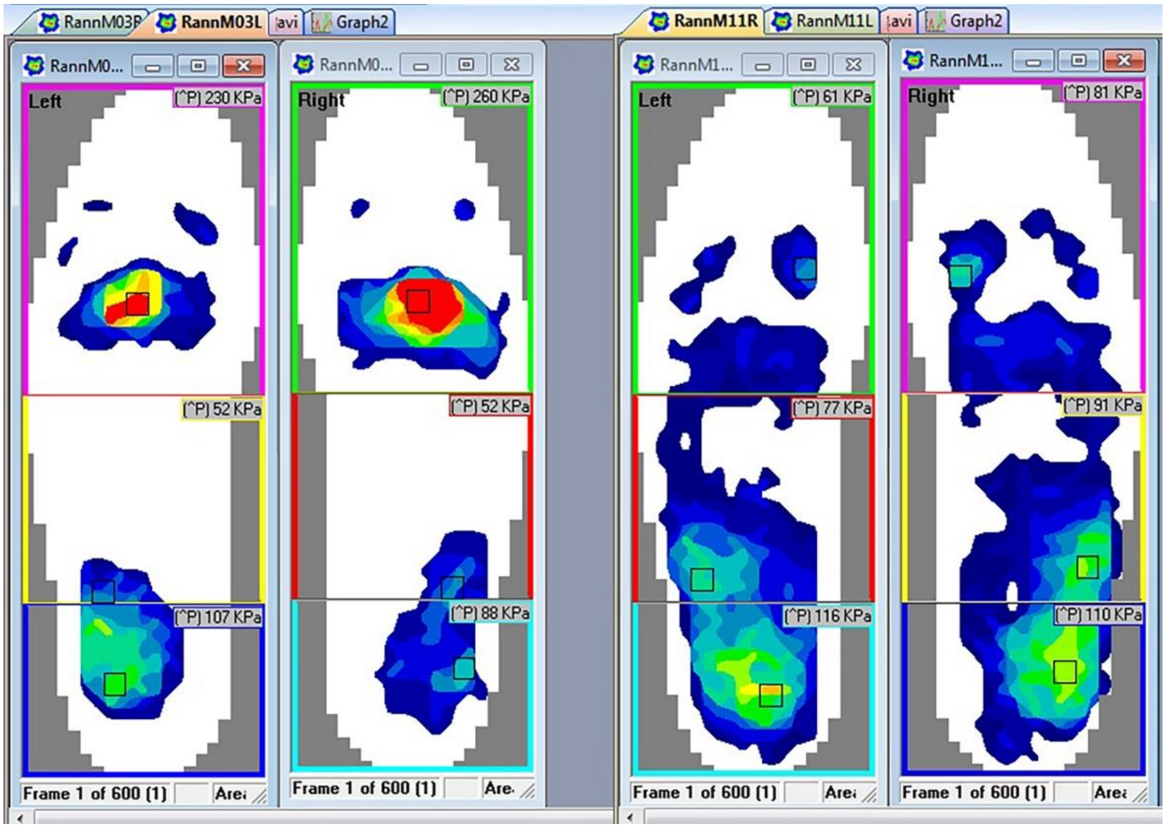
CHAPTER 4

RESULTS

4.1 Foot pressure and contact area data

A. Standing task

The average plantar pressure of the controlled shoe (all 12 subjects) is 65.53 ± (SD 17.5) KPa in forefoot region, 27.44 ± (SD 8.52) KPa in the midfoot region, and 46.73 ± (SD 16.89) KPa in the heel region. The average plantar pressure of the treatment shoe (all 12 subjects) is 32.61 ± (SD 9.7) KPa in the forefoot region, 35.03 ± (SD 8.38) KPa in the midfoot region, and 60.07 ± (SD 11.69) KPa in the heel region. Figure 4.1(a) Subject # 9 shows the plantar pressure of a subject wearing traditional high-heel shoes frame by frame. It shows that the forefoot pressure of this subject while wearing traditional high-heel shoes is 230 KPa for the left foot and 260 KPa for the right foot. The arch pressure of this subject is 52 KPa for the left foot and 52 KPa for the right foot. The heel pressure of this subject is 107 KPa for the left foot and 88 KPa for the right foot. Figure 4.1(b) illustrates the plantar pressure of a subject wearing shoes according to the proposed design frame by frame. It shows that the forefoot pressure of this subject while wearing proposed shoe design is 61 KPa for the left foot and 81 KPa for the right foot. The arch pressure of this subject is 77 KPa for the left foot and 91 KPa for the right foot. The heel pressure of this subject is 116 KPa for the left foot and 110 KPa for the right foot. Compared to wearing a traditional high heel, the forefoot average peak pressure is reduced and the pressure at the arch and heel is increased while the subject wears the proposed shoe. This is the trend, which is found in all subjects.



(a) An Illustration of the plantar Pressure Data of a Subject Wearing a Traditional High-Heel Shoe

(b) An Illustration of the Plantar Pressure Data of a Subject Wearing Shoes of a Subject Wearing Shoes of the Proposed Design.

Figure 4.1: The Comparison of Plantar Pressure Between the Controlled Shoe and the Treatment Shoe.

The plantar pressure for each participant and experimental condition is shown in Fig. 4.3. Fig 4.2 illustrates the comparison of the predicted average log pressure in different foot regions during standing task. The forefoot log pressure when participants wore the treatment shoes was significantly lower than when they wore the controlled shoes ($p<0.001$), as illustrated in Figure 4.2, Table 4.1 and Table 4.2. The proposed shoe reduced predicted plantar log pressure from 4.15 ± (SE 0.043) to 3.45 ± (SE 0.043) in forefoot region.

According to the Table 4.3, the interactions between the type of shoes (the controlled shoe and the treatment shoe) and foot regions (forefoot region, arch region, and heel region) is highly significant ($p<0.001$, $F=165.97$), indicating a significant difference of plantar pressure between the controlled shoe and treatment shoe at different a foot region (forefoot, arch and heel). Control shoes generated greatest plantar pressure found in the forefoot ($e^{4.15} = 63.434$) and the smallest plantar pressure in the arch ($e^{3.26} = 26.050$) (Table 4.1.), while the treatment shoes generated the greatest pressure in the heel ($e^{4.07} = 58.557$) and relatively uniform plantar pressure distribution (Table 4.2).

The predicted plantar pressure difference between two types of shoes during a standing task is calculated based on the equation shown in Table 4.4. The results were originally log pressure; exponential transformation was employed to change back to pressure data. The comparison showed that the proposed shoe design reduced the predicted average peak pressure of the forefoot region by 50.3% ($1-e^{-0.7} = 0.503$), and increased the pressure of the midfoot by 31% ($e^{0.27} = 0.31$) and heel by 34% ($e^{0.3}= 0.34$).

Control Heels					
Foot Regions	Est. Mean	SE	Lower C.L.	Upper C.L.	p-value
Forefoot	4.15	0.043	4.04	4.26	<0.0001
Arch	3.26	0.043	3.15	3.37	<0.0001
Heel	3.77	0.043	3.67	3.88	<0.0001

Table 4.1: Log Pressure of Left Foot Regions When Subject Wearing Control Heels during Standing Task.

Treatment Heels					
Foot Regions	Est. Mean	SE	Lower C.I.	Upper C.I.	p-value
Forefoot	3.45	0.043	3.34	3.55	<0.0001
Arch	3.53	0.043	3.42	3.63	<0.0001
Heel	4.07	0.043	3.97	4.18	<0.0001

Table 4.2: Log Pressure of Left Foot Regions When Subject Wearing Treatment Heels during Standing Task.

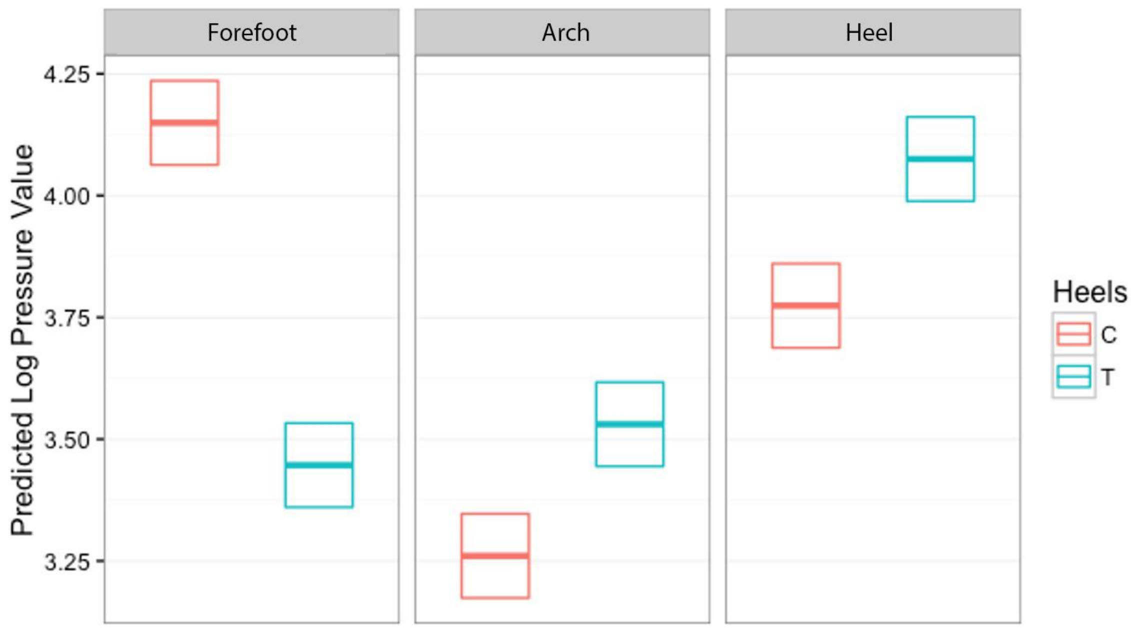


Figure 4.2. Predicted Value and Confidence Interval (95%) of Log Pressure for Different Heels and Left Foot Regions During a Standing Task.

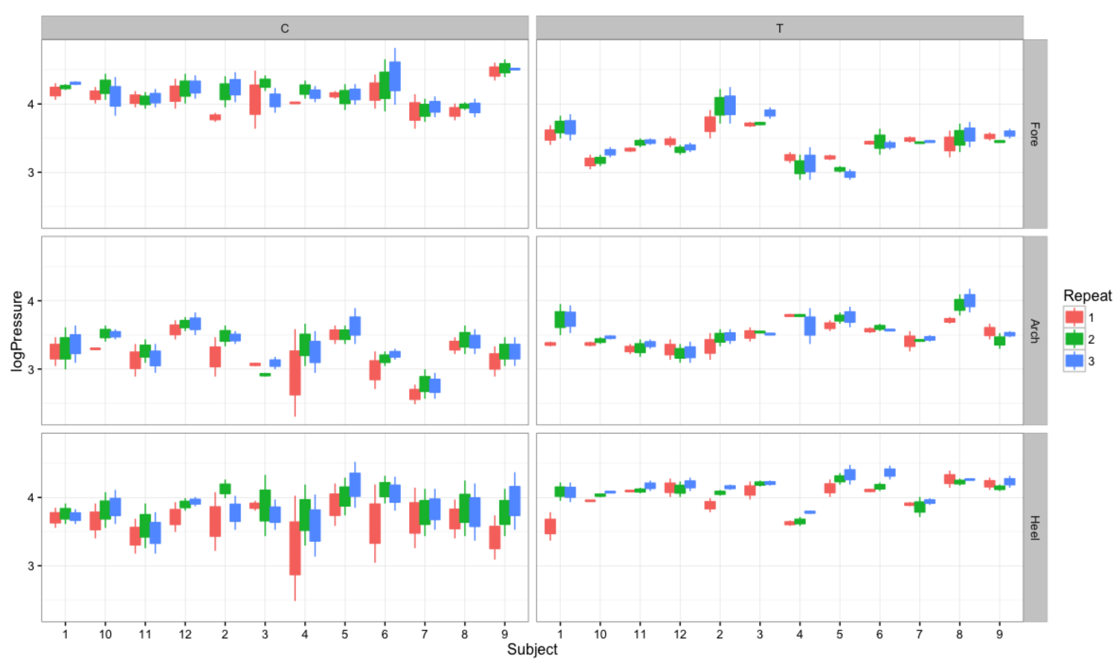


Figure 4.3: The Pressure Comparison Between the Treatment and the Controlled Shoe at Three Foot Regions During a Standing Task for Each Subject. Red Box - First Repetition of Standing Task; Green Box - Second Repetition of Standing Task; Blue Box - Third Repetition of Standing Task; C

- Controlled Shoe; T - Treatment Shoe; Fore - Forefoot Region; Arch - Arch Region; Heel - Heel Region.

	F Value	Degree of Freedom	Degree of Freedom (Residual)	P-value
Type of shoes	0.95	1	11	0.35
Foot regions	155.49	2	355	< 0.001
Right and left feet	19.39	1	355	< 0.001
Interactions between Type of shoes and Foot regions	165.97	2	355	< 0.001

Table 4.3: Analysis of Variance (ANOVA) of Fixed Effect for the Pressure Data of Standing Task

	Estimate value	Standard Error	Degree of Freedom	T Value	P-value
$\hat{\beta}_0$	4.20555	0.04489	59.3	93.687	<0.001
$\hat{\beta}_1$	-0.70263	0.05768	29.5	-12.182	<0.001
$\hat{\beta}_2$	-0.88885	0.04430	403.0	-20.063	<0.001
$\hat{\beta}_3$	-0.37532	0.04430	403.0	-8.471	<0.001
$\hat{\beta}_4$	-0.11264	0.02558	403.0	-4.404	<0.001
$\hat{\beta}_5$	0.97277	0.06265	403.0	15.526	<0.001
$\hat{\beta}_6$	1.00367	0.06265	403.0	16.019	<0.001

Table 4.4: Fixed Effect Summary Table of Pressure Data of a Standing Task. The Linear Fit Equation for log(pressure) of Standing Task: log(pressure) = $\widehat{\beta}_0 + \widehat{\beta}_1$ * "shoe type = Treatment" + $\widehat{\beta}_2$ * "area= Arch" + $\widehat{\beta}_3$* "area= Heel" + $\widehat{\beta}_4$ * "Foot = Right" + $\widehat{\beta}_5$ * "shoe type = Treatment" * "area= Arch" + $\widehat{\beta}_6$ * "shoe type = Treatment" * "area= Heel"

Table 4.5 shows the random variance component for this statistical model. Residual random effect (variance within one subject of a certain heel at certain replicate) accounts for 87.8% of unexplained variance, while subject (subject-to-subject variance) and heels (control-treatment heels variance) account for 2.7% and 9.5% respectively. Replicate-to-replicate variance is zero, indicating clustering of observations due to the replicates did not help explain any of the variability in the pressure.

	Variance	Variance Percentage (%)
Replicate	0	0
Heels	0.008	9.5
Subject	0.002	2.7
Residual	0.071	87.8

Table 4.5: Variance Component Table of Random Effect for the Pressure Data of Standing Task

It is worth mentioning that the pressure data discussed above are all for left foot. Coefficient for right foot is -0.11264 (p-value <0.001) according to Table 4.4. The predicted pressure will be multiplied by a factor of $e^{-0.11264}$, changing from left foot to right foot and keeping other variables the same. Right foot pressure is predicted to be 89% of the left foot pressure, decreasing by 11%.

In addition to foot pressure, this study also computed the contact area for each participant and condition (Figure 4.5). Fig. 4.4 illustrates the comparison of the predicted average contact area in different foot regions during a standing task. The predicted arch contact area when participants wore the treatment shoes was significantly higher than when they wore the controlled shoes (p<0.001), as illustrated in Figure 4.4, Table 4.6 and Table 4.7. The proposed shoe increased predicted contact area from 7.25 ± (SE 1.160) to 32.11 ± (SE 1.160) in arch region. There is a decrease (from 33.85 to 27.29) in forefoot region and an increase (from 21.95 to 28.83) in heel as well. According to Table 4.8, the interactions between types of shoes and foot regions have relatively small p-value (p value <0.001,

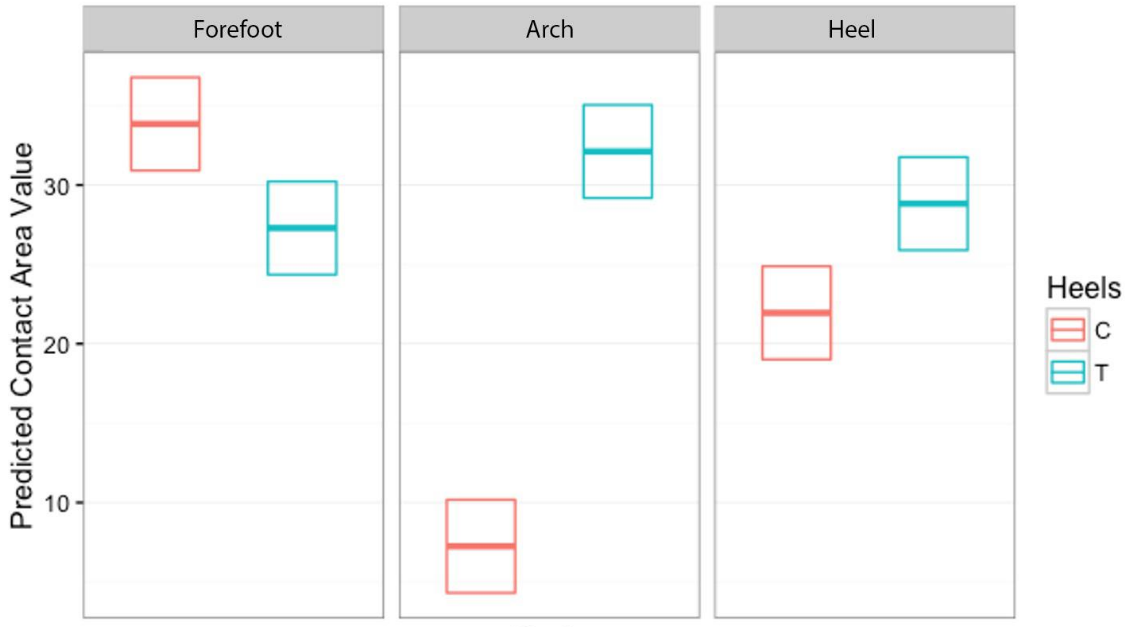


Figure 4.4. Predicted Value and Confidence Interval (95%) of Contact Area for Different Heels and Left Foot Regions during a Standing Task.

F=379.63), indicating a significant difference in contact area between the controlled shoe and treatment shoe at different foot regions (forefoot, arch and heel). Like previous pressure model, control shoes generated greatest contact area found in the forefoot (33.85) and the smallest contact area in the arch (7.25) (Table 4.1.), while the treatment shoes generated the greatest contact area in the arch (32.11) and relatively uniform contact area distribution (Table 4.2).

The predicted contact area difference between two types of shoes during a standing task is calculated based on the data and the equation shown on Table 4.9. It shows that the proposed design increases the contact area of the mid-foot region by 372.7% (24.86 / 6.67), and heel by 32.2% (6.88/21.37), compared to the control shoe.

Control Heels					
Foot Regions	Est. Mean	SE	Lower C.L.	Upper C.L.	p-value
Forefoot	33.85	1.160	30.92	36.78	<0.0001
Arch	7.25	1.160	4.32	10.18	<0.0001
Heel	21.95	1.160	19.01	24.88	<0.0001

Table 4.6: Contact Area of Left Foot Regions When Subject Wearing Control Heels during Standing Task.

Treatment Heels					
Foot Regions	Est. Mean	SE	Lower C.I.	Upper C.I.	p-value
Forefoot	27.29	1.160	24.36	30.22	<0.0001
Arch	32.11	1.160	29.18	35.05	<0.0001
Heel	28.83	1.160	25.89	31.76	<0.0001

Table 4.7: Contact Area of Left Foot Regions When Subject Wearing Treatment Heels during Standing Task.

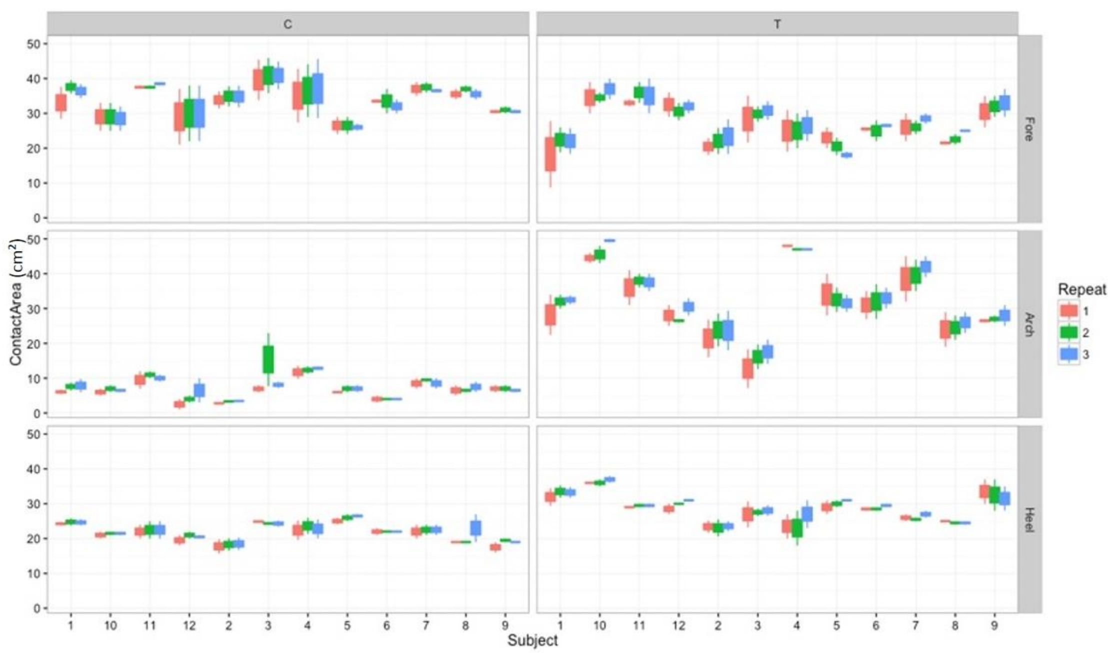


Figure 4.5: The Contact Area Comparison Between the Treatment and The Controlled Shoe at Three Foot Regions During a Standing Task for Each Subject. Red Box - First Repetition of Standing Task; Green Box -Second Repetition of Standing Task; Blue Box - Third Repetition of Standing Task; C - Controlled Shoe; T - Treatment Shoe; Fore - Forefoot Region; Arch, Arch Region; Heel, Heel Region.

	F Value	Degree of Freedom	Degree of Freedom (Residual)	p-value
Type of shoes	31.29	1	11	0.0016
Foot regions	181.14	2	355	<0.001
Right and left feet	6.03	1	355	0.0145
Interactions between Type of shoes and Foot regions	379.63	2	355	<0.001

Table 4.8. Analysis of Variance (ANOVA) of Fixed Effect for the Contact Area of a Standing Task

	Estimate value	Standard Error	Degree of Freedom	T Value	p-value
$\hat{\beta}_0$	33.2741	1.1828	33.8	28.130	<0.001
$\hat{\beta}_1$	-6.5578	1.6399	31.3	-3.999	<0.001
$\hat{\beta}_2$	-26.5994	0.8092	403.0	-32.870	<0.001
$\hat{\beta}_3$	-11.9001	0.8092	403.0	-14.705	<0.001
$\hat{\beta}_4$	1.1479	0.4672	403.0	2.457	0.014433
$\hat{\beta}_5$	31.4244	1.1444	403.0	27.459	<0.001
$\hat{\beta}_6$	13.4362	1.1444	403.0	11.741	<0.001

Table 4.9. Fixed Effect Summary Table of Contact Area of Standing Task. The Linear Fit Equation For Contact Area Of Standing Task: contact area = $\widehat{\beta}_0 + \widehat{\beta}_1$ * "shoe type = Treatment" + $\widehat{\beta}_2$ * "area= Arch" + $\widehat{\beta}_3$* "area= Heel" + $\widehat{\beta}_4$ * "Foot = Right" + $\widehat{\beta}_5$ * "shoe type = Treatment" * "area= Arch" + $\widehat{\beta}_6$ * "shoe type = Treatment" * "area= Heel"

Table 4.10 shows the random variance component for this statistical model. Residual random effect (variance within one subject of a certain heel at certain replicate) accounts for 66% of unexplained variance, while heels (control-treatment heels variance) account for 34%. Repeat-to-repeat variance and subject-to-subject variance are zero, indicating clustering of observations due to the replicates or the subjects did not help explain any of the variability in the contact area.

	Variance	Variance Percentage (%)
Replicate	0	0
Heels	12.21	34
Subject	0	0
Residual	23.57	66

Table 4.10: Variance Component Table of random for the contact area data of standing task

The contact area data discussed above are all for left foot. Coefficient for right foot is 1.1479 (p-value = 0.014) according to Table 4.9. The predicted contact area will increase by 1.1479, changing from left foot to right foot and keeping other variables the same.

B. Walking task

Fig. 4.6 illustrates the comparison of the predicted average log pressure of left foot between the controlled and the treatment shoe during a walking task. Fig. 4.7 illustrates the comparison of the average log pressure of all 12 subjects in detail during a walking task. . The forefoot log pressure when participants wore the treatment shoes was significantly lower than when they wore the controlled shoes ($p<0.001$), as illustrated in Figure 4.6, Table 4.11 and Table 4.12. The proposed shoe reduced predicted plantar log pressure from 5.30 ± (SE 0.068) to 4.88 ± (SE 0.068) in forefoot region. According to the table 4.14, the interactions between types of shoes (the treatment shoe and the controlled shoe) and the foot regions is highly significant ($p<0.01$, $F=219.59$), indicating a significant difference of plantar pressure between the controlled shoe and treatment shoe at different foot regions (forefoot, arch and heel). Control shoes generated greatest plantar pressure found in the forefoot ($e^{5.30} = 200.337$) and the smallest plantar pressure in the arch ($e^{3.08} = 21.758$) (Table 4.11.), while the treatment shoes although also generated the greatest pressure in the forefoot ($e^{4.88} = 131.631$) but relatively uniform plantar pressure distribution with all three regions. (Table 4.12).

The predicted plantar pressure difference between two types of shoes during a walking task is calculated based on the equation shown on Table 4.14. The results were originally log pressure; exponential transformation was employed to change back to pressure data. The comparison shows that the proposed shoe design reduces average peak pressures of the forefoot region by 34%(1-$e^{-0.42}$),, and increases the pressure of mid-foot by 32%($e^{0.28}$-1), and the heel by 52%.($e^{0.42}$-1)

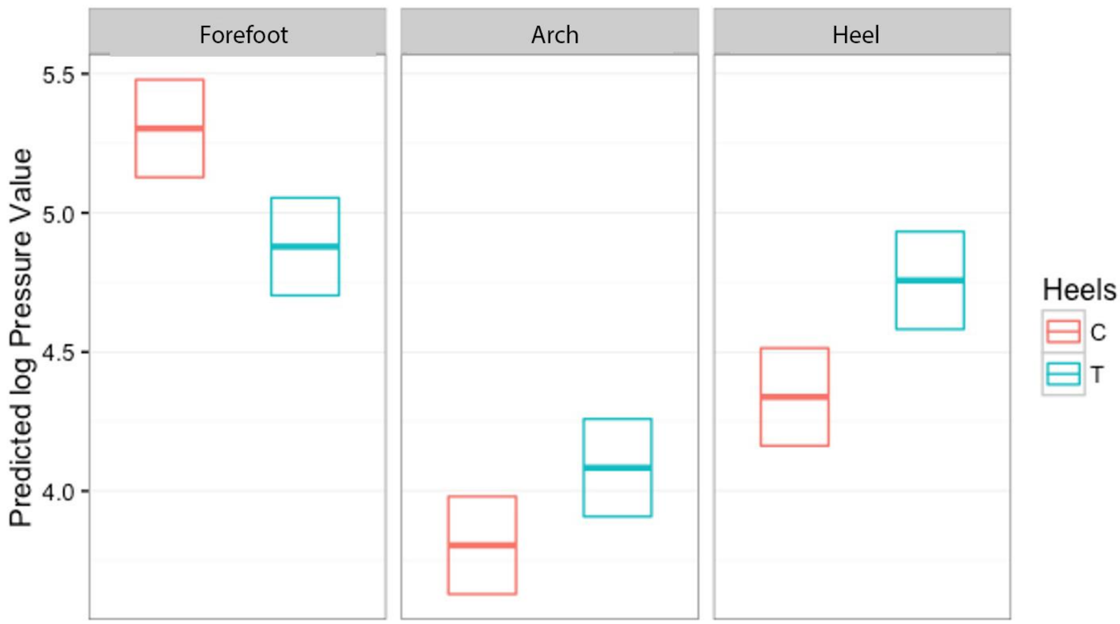


Figure 4.6. Predicted Value and Confidence Interval (95%) of log Pressure for Different Heels and Left Foot Regions during a Walking Task.

Control Heels					
Foot Regions	Est. Mean	SE	Lower C.L.	Upper C.L.	p-value
Forefoot	5.30	0.068	5.13	5.48	<0.0001
Arch	3.08	0.068	3.63	3.98	<0.0001
Heel	4.34	0.068	4.16	4.51	<0.0001

Table 4.11: Log Pressure of Left Foot Regions When Subject Wearing Control Heels during Walking Task.

Treatment Heels					
Foot Regions	Est. Mean	SE	Lower C.I.	Upper C.I.	p-value
Forefoot	4.88	0.068	4.70	5.05	<0.0001
Arch	4.08	0.068	3.91	4.26	<0.0001
Heel	4.75	0.068	4.58	4.93	<0.0001

Table 4.12: Log Pressure of Left Foot Regions When Subject Wearing Treatment Heels during Walking Task.

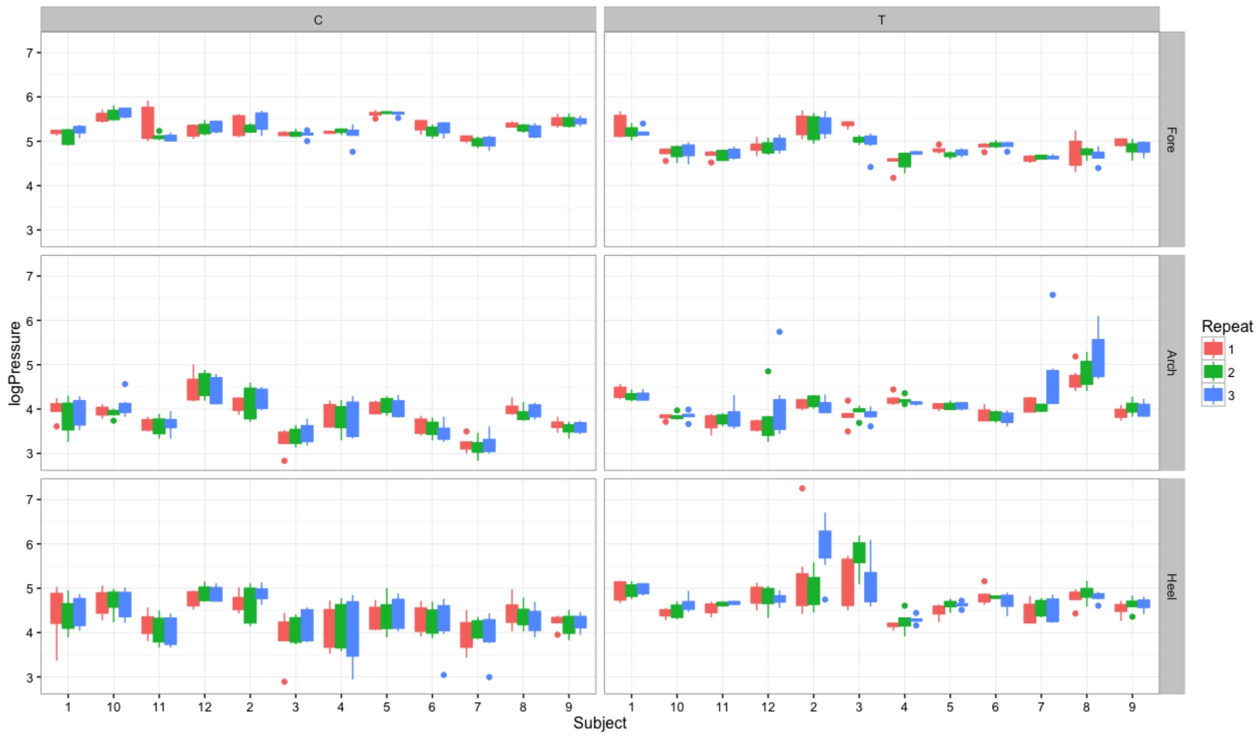


Figure 4.7: The Pressure Comparison Between The Treatment And The Controlled Shoe At Three Foot Regions During A Walking Task For Each Subject. Red Box, -First Repetition Of Walking Task; Green Box - Second Repetition Of Walking Task; Blue Box - Third Repetition Of Walking Task; C - Controlled Shoe; T, Treatment Shoe; Fore - Forefoot Region; Arch - Arch Region; Heel, Heel Region.

	F Value	Degree of Freedom	Degree of Freedom (Residual)	P-value
Type of shoes	1.08	1	11	0.3208
Foot regions	1414.39	2	1075	<0.01
Right and left feet	48.62	1	1075	<0.01
Interactions between Type of shoes and Foot regions	219.59	2	1075	<0.01

Table 4.13: Analysis Of Variance (ANOVA) Of Fixed Effect for the Pressure Data of a Walking Task.

	Estimate value	Standard Error	Degree of Freedom	T Value	P-value
$\hat{\beta}_0$	5.36479	0.06893	25.70	77.828	<0.001
$\hat{\beta}_1$	-0.42470	0.09098	12.90	-4.668	<0.001
$\hat{\beta}_2$	-1.49848	0.03051	1267.0	-49.122	<0.001
$\hat{\beta}_3$	-0.96509	0.03051	1267.0	-31.637	<0.001
$\hat{\beta}_4$	-0.12281	0.01761	1267.0	-6.973	<0.001
$\hat{\beta}_5$	0.70351	0.04314	1267.0	16.307	<0.001
$\hat{\beta}_6$	0.84353	0.04314	1267.0	19.553	<0.001

Table 4.14: Fixed Effect Summary Table of Pressure Data of Walking Task. The Linear Fit Equation For log(Pressure) Of Walking Task: log(pressure) = $\widehat{\beta}_0$ + $\widehat{\beta}_1$ * “shoe type = Treatment” + $\widehat{\beta}_2$ * “area= Arch” + $\widehat{\beta}_3$* “area= Heel” + $\widehat{\beta}_4$ * “Foot = Right” + $\widehat{\beta}_5$ * “shoe type = Treatment” * “area= Arch” + $\widehat{\beta}_6$ * “shoe type = Treatment” * “area= Heel”

Table 4.15 shows the random variance component for this statistical model. Residual random effect (variance within one subject of a certain heel at certain replicate and step) accounts for 66.6% of unexplained variance, while subject (subject-to-subject variance) and heels (control-treatment heels variance) account for 4.2% and 29.2% respectively. Replicate-to-replicate and step-to-step variance are zero, indicating clustering of observations due to the replicates or the steps did not help explain any of the variability in the pressure.

	Variance	Variance Percentage (%)
Step	0	0
Replicate	0	0
Heels	$4.408 *10^{-2}$	29.2
Subject	$6.421 *10^{-3}$	4.2
Residual	$1.005 *10^{-1}$	66.6

Table 4.15: Variance Component Table of Random For the Pressure Data of Walking Task

It is also worth mentioning that the pressure data discussed above are all for left foot. Coefficient for right foot is -0.1128 (p-value <0.001) according to Table 4.14. The predicted pressure will be multiplied by a factor of $e^{-0.1128}$, changing from left foot to right foot and keeping other variables the same. Right foot pressure is predicted to be 88% of the left foot pressure, decreasing by 12%.

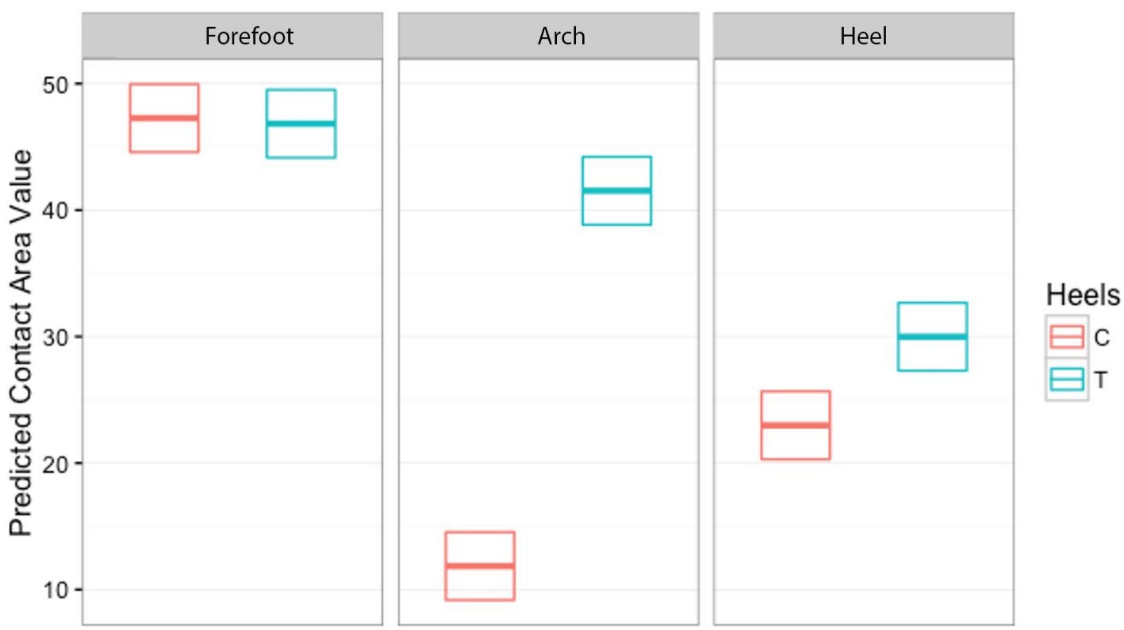


Figure 4.8 Predicted Value and Confidence Interval (95%) of Contact Area for Different Heels and Left Foot Regions during a Walking Task.

Fig: 4.8 illustrates the comparison of the contact area in different foot regions during a walking task. Fig. 4.9 illustrates the comparison of the contact area in different foot regions for all 12 subjects in detail during a walking task. The arch contact area when participants wore the treatment shoes was significantly higher than when they wore the controlled shoes ($p<0.001$), as illustrated in Figure 4.8, Table 4.16 and Table 4.17. The proposed shoe increased predicted contact area from 11.85 ± (SE 1.048) to 41.53 ± (SE 1.048) in arch region. According to the Table 4.18, the interactions between the types of shoes and foot regions have a small p-value ($p<0.001$, $F=1017.85$), indicating a significant difference of plantar pressure between the controlled shoe and treatment shoe at different foot regions (forefoot, arch and heel). Control shoes generated greatest contact area found in the forefoot (47.27) and the smallest contact area in the arch (11.85) (Table 4.16.), while the treatment shoes also generated the similar contact area in forefoot as control shoe (46.83) but a relatively uniform contact area distribution between forefoot and arch (Table 4.17).

The contact area difference between two types of shoes during a walking task is calculated based on the equation shown in Table 4.11. It shows that the proposed design increases the contact area of the mid-foot region by 237%(26.68/11.28), and heel by 31.3%(7.01/22.4) wearing high heels.

Control Heels					
Foot Regions	Est. Mean	SE	Lower C.L.	Upper C.L.	p-value
Forefoot	47.27	1.048	44.59	49.56	<0.0001
Arch	11.85	1.048	14.54	11.54	<0.0001
Heel	22.98	1.048	20.30	25.67	<0.0001

Table 4.16: Contact Area of Left Foot Regions When Subject Wearing Control Heels during Walking Task.

Treatment Heels					
Foot Regions	Est. Mean	SE	Lower C.I.	Upper C.I.	p-value
Forefoot	46.83	1.048	44.15	49.52	<0.0001
Arch	41.53	1.048	38.85	44.22	<0.0001
Heel	29.99	1.048	27.30	32.67	<0.0001

Table 4.17: Contact Area of Left Foot Regions When Subject Wearing Treatment Heels during Walking Task.

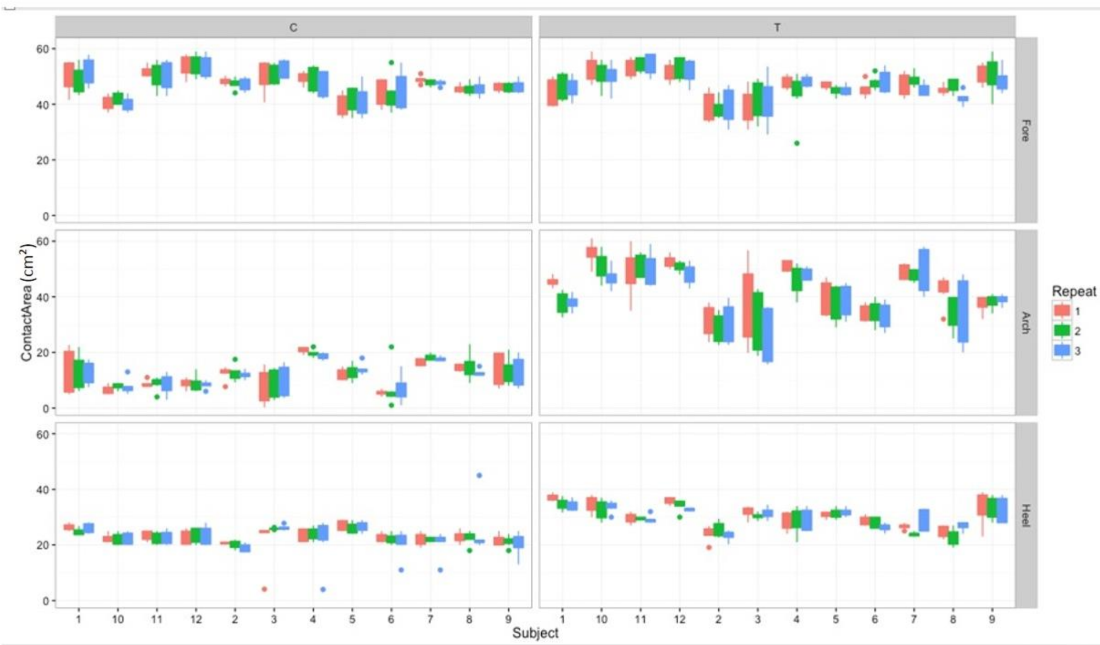


Figure 4.9: The Contact Area Comparison Between The Treatment And The Controlled Shoe At Three Foot Regions During A Walking Task For Each Subject. Red Box - First Repetition Of Walking Task; Green Box -Second Repetition Of Walking Task; Blue Box - Third Repetition Of Walking Task; C - Controlled Shoe; T - Treatment Shoe; Fore - Forefoot Region; Arch - Arch Region; Heel - Heel Region.

	F Value	Degree of Freedom	Degree of Freedom (Residual)	P-value
Type of shoes	75.25	1	11	<0.001
Foot regions	2309.35	2	1075	<0.001
Right and left feet	16.35	1	1075	<0.001
Interactions between Type of shoes and Foot regions	1017.85	2	1075	<0.001

Table 4.18: Analysis of Variance (ANOVA) of Fixed Effect for the Contact Area of Walking Task.

	Estimate value	Standard Error	Degree of Freedom	T Value	P-value
$\hat{\beta}_0$	46.6989	1.0577	26.50	44.153	<0.001
$\hat{\beta}_1$	-0.4426	1.4492	12.90	-0.305	0.765
$\hat{\beta}_2$	-35.4200	0.4917	1267.0	-72.032	<0.001
$\hat{\beta}_3$	-24.2908	0.4917	1267.0	-49.399	<0.001
$\hat{\beta}_4$	1.1478	0.2839	1267.0	4.043	<0.001
$\hat{\beta}_5$	30.1196	0.6954	1267.0	43.312	<0.001
$\hat{\beta}_6$	7.4472	0.6954	1267.0	10.709	<0.001

Table 4.19: Fixed Effect Summary Table of Contact Area of Walking Task. The Linear Fit Equation for Contact Area of Walking Task: contact area = $\widehat{\beta}_0$ + $\widehat{\beta}_1$ * "shoe type = Treatment" + $\widehat{\beta}_2$ * "area= Arch" + $\widehat{\beta}_3$* "area= Heel" + $\widehat{\beta}_4$ * "Foot = Right" + $\widehat{\beta}_5$ * "shoe type = Treatment" * "area= Arch" + $\widehat{\beta}_6$ * "shoe type = Treatment" * "area= Heel"

Table 4.20 shows the random variance component for this statistical model. Residual random effect (variance within one subject of a certain heel at certain replicate and step) accounts for 69% of unexplained variance, while subject (subject-to-subject variance) and heels (control-treatment heels variance) account for 1.5% and 29.5% respectively. Replicate-to-replicate and step-to-step variance are zero, indicating clustering of observations due to the replicates or the steps did not help explain any of the variability in the pressure.

It is worth mentioning that the contact area data discussed above are all for left foot. Coefficient for right foot is 1.1478 (p-value <0.001) according to Table 4.19. The predicted contact area will have an increase of 1.1478, changing from left foot to right foot and keeping other variables the same.

	Variance	Variance Percentage (%)
Step	0	0
Replicate	0	0
Heels	11.151	29.5
Subject	0.580	1.5
Residual	26.114	69

Table 4.20: Variance Component Table of Random for the Contact Area Data of Walking Task

4.2 Subjective questionnaire data

According to the feedback of the subjective questionnaire, the mean comfort rating in the proposed shoe was 58.5% better than in the traditional high heels, indicating the proposed high heel is more comfortable than traditional high heels (Figure 4.11). Fig 4.10 illustrates the comparison of the comfort rating for each test condition. In comparison with the controlled shoes, the proposed shoe improved comfort rating is from 2.5 ± (SD 0.75) to 5.4 ± (SD 1.11) in forefoot region, from 4.2 ± (SD 1.18) to 5.3 ± (SD 1.36) in the midfoot region, and from 3.3 ± (SD 1.54) to 5.2 ± (SD 1.34) in heel region (Figure 4.10). All 13 subjects reported that they felt the plantar pressure at the forefoot region was reduced while wearing the treatment shoes. They also reported that they didn't feel pain at forefoot region while wearing the treatment shoes during a standing task. In contrast, all of them reported that pain occurred at the forefoot region while wearing controlled shoes. Their comments also showed that they felt acceptable support at the arch and heel region when they wore the treatment shoes.

Some subjects gave negative feedback for the proposed shoes. For example, Subject #5 said, "For me, whether I would buy your shoes depends on whether it is beautiful enough. I am not sure whether the treatment shoes with angle adjustment system would be beautiful enough for me." Subject #2 said, "I don't like the ankle strap design of the shoe. It makes my ankle uncomfortable." Subject #11 said, "Just to be honest, your testing shoe is really heavy, which makes me walk too slow." Subject #9 said, "Your shoe makes my feet keep sliding down."

This investigation hypothesizes that such a new high-heel design may improve foot comfort by reducing peak plantar pressure and redistributing plantar pressure in the high heel compared to traditional high heeled shoes. The data collected confirms this hypothesis. According to the feedback of subjects participating in the subjective questionnaire, the proposed shoe was 58.5% more comfortable than traditional high heels (Figure 4.11). In comparison with the controlled shoe, the proposed shoe improved the comfort rating for all

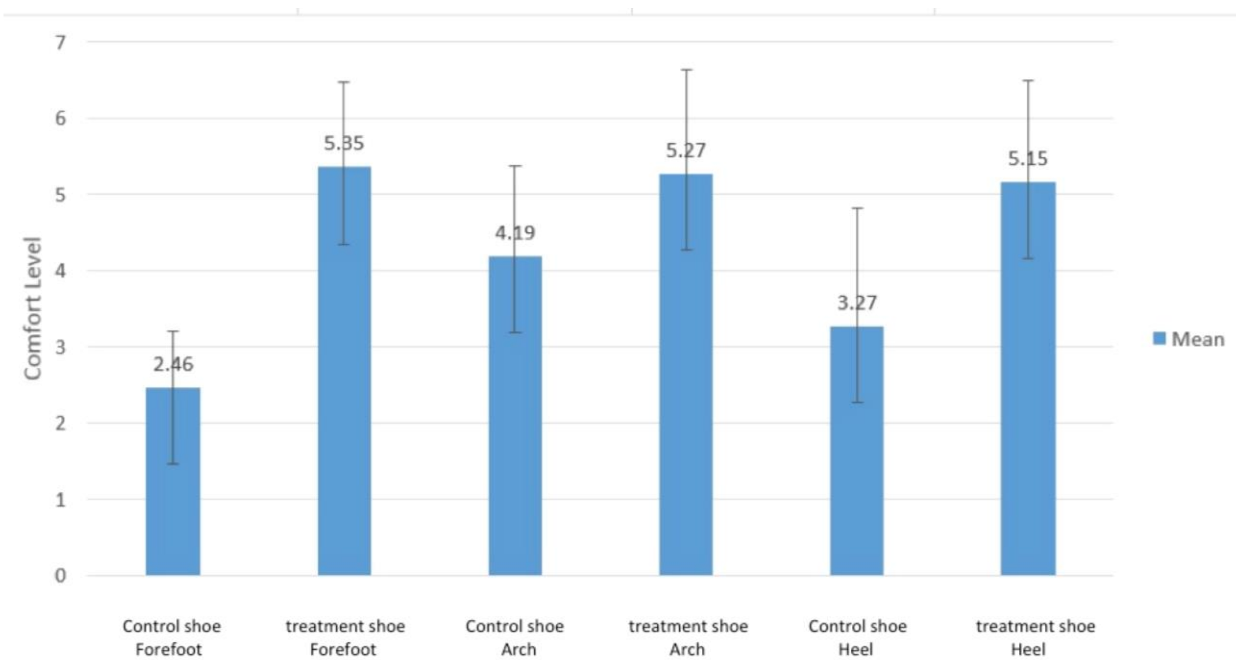


Figure 4.10: The Comparison of Comfort Levels Between the Treatment and the Controlled Shoe for Three Foot Regions.

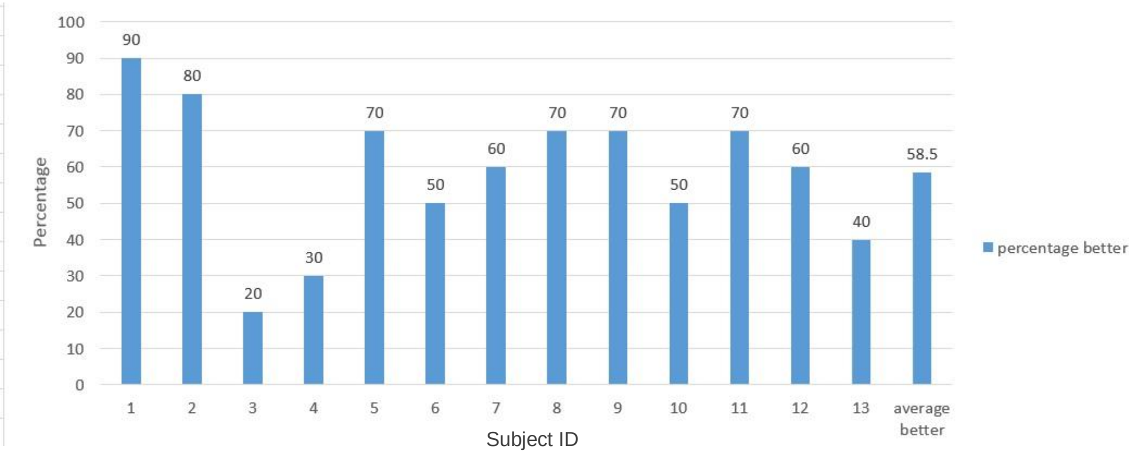


Figure 4.11: The Comparison of Comfort Rating Between the Treatment and the Controlled Shoe.

of the three foot regions, from 2.5 ± (SD 0.75) to 5.4 ± (SD 1.11) in the forefoot region, 4.2 ± (SD 1.18) to 5.3 ± (SD 1.36) in the mid-foot region, and from 3.3 ± (SD 1.54) to 5.2 ± (SD 1.34) in the heel region), as shown in Figure 4.10.

The results also show that the automatically rotating outsole prevented pain on the ball of foot by redistributing the load from the wearer's forefoot to their mid-foot and heel. When comparing with the controlled shoe condition during a standing task, it shows that the proposed shoe design reduces average peak pressure of the forefoot region by 50.3%, and increases the pressure of the mid-foot by 31% and heel by 34% (Figure 4.2). In comparison with the controlled shoe condition during a walking task, it shows that the proposed shoe design reduces average peak pressure of the forefoot region by 34%, and increases the pressure of mid-foot by 32% and heel by 52% (Figure 4.6). Both results from the mid-foot and the heel region explain the fact that a certain portion of the plantar pressure from the forefoot region is redistributed to the mid-foot and the heel region.

The hypothesis that the increasing foot contact area could reduce peak plantar pressure by providing more support to the foot is also supported. When comparing to the controlled shoe condition during a standing task, it shows that the proposed design increases the contact area of mid-foot region by 372.7% and heel by 32.2% compared to the controlled shoe (Figure 4.4). In comparison with the controlled shoe condition during a walking task, it shows that the proposed design increases the contact area of the mid-foot region by 237% and heel by 31.3% compared to the wear controlled shoe (Figure 4.8).

CHAPTER 5

CONCLUSION

In this thesis, an automatic heel height and angle adjustment system for a dress shoe was developed for improved foot comfort. This was done by redistributing part of plantar pressure from the ball of the foot region to mid-foot and heel region. The high heel design is based on a uniform plantar pressure distribution of human-walking dynamics. The pressure data were collected from the pressure sensors.

The findings of this study demonstrate that increasing the heel height increases the forefoot pressure and discomfort during standing and walking. In this investigation, it hypothesizes that a proposed high-heeled shoe design utilizing the adjustable heel height system, the automatically rotating outsole, and the strategy of increasing foot contact area can improve foot comfort by reducing peak plantar pressure and redistributing plantar pressure in a high-heeled shoe as compared to conventional high-heeled shoes. Both the qualitative and quantitative data from this study are in support of this hypothesis. According to the qualitative data, the proposed shoe improves foot comfort by 58.5% compared to traditional high heels. By comparing the plantar pressure data during a standing task, it shows that the proposed shoe can reduce the average peak pressure of the forefoot region by 50.3% and increase the mid-foot pressure by 31% and heel pressure by 34%. During a walking task, it shows that the proposed shoe can reduce the average peak pressure of the forefoot region by 34% and increase the mid-foot pressure by 32% and the heel pressure by 52%. Furthermore, it shows that the proposed shoe increases the average mid-foot contact area by 372.2% and heel by 32.2% during a standing task. The proposed shoe increases the average mid-foot contact area by 237% and heel by 31.3% during a walking task. These results highlight the benefit of the proposed shoe and also prove that the proposed shoes offer better foot comfort by reducing plantar pressure in the forefoot compared to wearing traditional high heels.

However, further design efforts need to be made to make the prototype more aesthetically acceptable as a fashion item. In addition, future studies need to improve ways to adjust the shoe angle and heel height with more ease and convenience. Some subjects' feedbacks also suggest that the proposed shoe existed the problem of sliding forward. This problem is needed to be solved in the future study. Furthermore, the potential of using a soft robotics system to improve foot comfort needs to be further studied. This idea is not fully investigated in this study because of limited time, but such novel technology should be fully developed for improving the foot comfort of a high-heeled shoe. For example, it is necessary to explore the possibility of using continuous structure from the soft robotics mechanism as the dynamic arch support on the high heeled shoes, which could fully mimic the female subjects' arch shape. Compared to the proposed shoe developed in this study, the idea of using the continuous structure on the arch region might provide even better foot comfort and pressure distribution. Further design efforts also need to be made to make the prototype shoes have the possibility of commercialization by reducing the weight and bulkiness of added electronics. Future work also includes the exploration of feasible and optimal ways of mass production.

There are several limitations in this study: First, all research was conducted in a laboratory setting. Also, all walking and standing tasks were performed for only 1 hour. In real life, each subject might wear high heels longer than 1 hour. Furthermore, some subjects have more experience wearing high heels than other subjects. The type of the strap from the controlled shoe and the treatment shoe is not fully controlled, which might have different impact on the result of the data. For example, the different type of strap might cause different stress impact on the forefoot region of the subjects' feet. However, the plantar pressure and contact area data collected from the subjects and the subject's feedback about the comfort rating of the proposed design could give some new insight about how to design a more ergonomic and commercially viable high-heel. This study analyzed only plantar pressure in the left foot with a small group of participants and found statistical significance in a few variables. The analysis also showed limited statistical power to explain causal effect between treatment and dependent variable, which suggests future studies need to be done with more rigorous and thorough experiment control with a large population and analysis of more biomechanical variables of both feet for validation of the findings of this study. Therefore, application and generalization of the findings of this study needs caution.

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