Prototype Development of a Joint Padded Metatarsal Cup to Enhance Female Foot Musculoskeletal Safety

By

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Declaration

This is to certify that the thesis work entitled "*Prototype Development of a Joint Padded Metatarsal Cup to Enhance Female Foot Musculoskeletal Safety*" has been carried out by Abu Jor in the Department of Industrial Engineering and Management, Khulna University of Engineering & Technology, Khulna, Bangladesh. The above thesis work or any part of this work has not been submitted anywhere for the award of any degree or diploma.

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Abstract

This study investigated the feasibility of joint padded metatarsal cup on plantar pressures and stress distribution in the bone alignment of female foot with high heeled footwear during balanced standing. The aim of this study is to redistribute the plantar pressure away from the medial side of the forefoot. A joint padded metatarsal cup was developed from medium soft ethylene vinyl acetate (EVA) and very soft ethylene propylene diene monomer (EPDM) neoprene sponge. The participants of three categories were selected for the study. The peak plantar pressure and a radiographic assessment of foot musculoskeletal alignment were carried out. The results showed that the magnitude of load on medial forefoot area could be effectively reduced by inserting joint of soft materials on metatarsal region. Hence load on hallux could also be reduced satisfactorily which could resist the hallux valgus deformity. A comparison of conventional system and jointing materials separately with the developed prototype was made and found that the developed prototype of joint padded metatarsal cup (JPMC) provides more relaxation of plantar pressure and musculoskeletal safety and confirms more comfort on hypothesis test. The concept of joint padded metatarsal base should therefore be considered to help in designing musculoskeletal safety footwear.

Keywords: metatarsal cup; female foot; plantar pressure; hallux; musculoskeletal safety; comfort;

Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATION

EVA	:	Ethylene Vinyl Acetate
MSEVA	:	Medium Soft EVA
EPDM	:	Ethylene Propylene Diene Monomer
VSEPDM	:	Very Soft EPDM
JPMC	:	Joint Padded Metatarsal Cup
HVA	:	Hallux Valgus Angle
IMA	:	Inter-Metatarsal Angle
MF	:	Medial Forefoot
CF	:	Central Forefoot
LF	:	Lateral Forefoot
H	:	Hallux
CH	:	Central Heel
COP	:	Centre of Pressure

CHAPTER I

Introduction

1.1 Introduction

The increasing rate of high heel use in women presents a unique opportunity to analyse the foot biomechanics on musculoskeletal safety in female groups. The heel elevation initiates more exertion from lower leg muscles and cause worse utilitarian versatility which start at 7cm and footwear of heel more than 7cm could cause heavy impact to human balance system [1]. American Podiatric Medical Association revealed that 49% of women use high heels among them 71% of women have painful experience [2]. Previous research have exhibited that, use of high heel footwear produces extra muscular tension on the foot and ankle to manage a balance walking pattern and lead to problems like muscle fatigue, constricts blood vessel, low back pain, forefoot pain, alters lower-extremity joint function, ankle sprain, hallux valgus, corns, calluses etc. [3-5]. A survey on high heeled revealed that the most frequent deformations were 71% of hallux valgus, 50% of hammer toe and 18% of bunionettes [6].

As the heel height increase, pressure under the forefoot is also found to increase significantly and the centre of pressure shifted from the mid-foot to the forefoot position. Heel elevation from 0 to 10.2 cm can reduce the contact area by 26% and increase the internal stresses of foot bones [7]. But Cong et al. showed that the peak pressure shifted towards the medial forefoot and the hallux as the heel height increased from 3 to 7 cm and could be a reason of hallux deformity [8]. Hallux valgus deformation was believed to be caused by an irritated flexor hallucis muscle at the first metatarsophalangeal joint [9], particularly when external tensions insist the hallux to abduct and thus cause hallux valgus deformity. In high heels, plantar pressure decreased under the heel and mid-foot and caused an increase in peak pressures of 34% in the medial forefoot (metatarsal 1) whereas in the central forefoot (metatarsals 2–4) 30% compared with the low heels [10].

Metatarsal pads can reduce pain and improve the score of the American Orthopaedic foot & ankle society to 24.2 points in all patients, among women 19 points, and among men 29 points [11]. Insertion of thick soft foam could reduce pick pressure by 26%, impact force by 27% and force time integral by 20% in comparison with the condition without embed in a high heeled footwear [12]. Luximon et al. used three types of pad like bio gel, polyurethane and EVA to redistribute the forefoot pressure, among them polyurethane pad showed the lowest peak pressure and reduced pressure by 35.54% [13]. An U shape 7mm semi compressed metatarsal pad cut-out to the second metatarsal head can reduce peak pressure by 25% [14]. Felt padding of 7mm thickness could give a greater reduction of plantar force than 5mm compared to a control of no felt padding [15].

The articles published so far have connected with the impact of high-heeled footwear on gait, foot loading, or the activity of selected muscle groups. Despite the high frequency of the structural and functional changes of forefoot, only few research and guidelines about load redistribution at forefoot are published. The aim of this study is to decentralize the forefoot load with introducing a joint padded cup at metatarsal portion and enhance musculoskeletal safety and comfort.

1.2 Objectives of the Research Work

- To develop a joint padded cup for metatarsophalangeal area to redistribute peak pressure in high heeled footwear.
- To analyse and compare the impact of high heels on kinetic and foot bone alignment
- To test a hypothesis: Designed footwear is more comfortable than the conventional one

CHAPTER II

Literature Review

2.1 Anatomy of Foot

The anatomy of foot is the structure of feet which is so important to design footwear. The structural strength and mechanical complexity is combined by the human foot. The ankle acts as the absorber of shock, foundation, and engine of propulsion. The foot can sustain tremendous pressure (several tons over the course of a one-mile run) and provides resiliency and flexibility.

The foot and ankle contain [16]:

- 26 bones;
- 33 joints;
- More than 100 muscles, tendons (fibrous tissues that connect muscles to bones), and ligaments (fibrous tissues that connect bones to other bones); and
- A network of blood vessels, nerves, skin, and soft tissue.

These parts and components work jointly to provide the body with balance, mobility and support. A structural defects or flaw in any one part can lead in the development of problems elsewhere in the body. Abnormalities in various parts of the body can create problems in the feet.

Parts of the Foot

From the structural point of view, the foot can be classified into three main parts: the forefoot, the mid-foot, and the hind-foot.

The forefoot is composed of the five toes called phalanges those are connected with long bones called metatarsals. Each phalanx is made up of several small bones. The big toe or hallux has two phalanx bones; distal and proximal and one joint called the inter-phalangeal joint. The hallux toe articulates with the head of the first metatarsal and is called the first metatarsophalangeal joint. Sesamoids are two tiny, round bones positioned beneath the first metatarsal head.

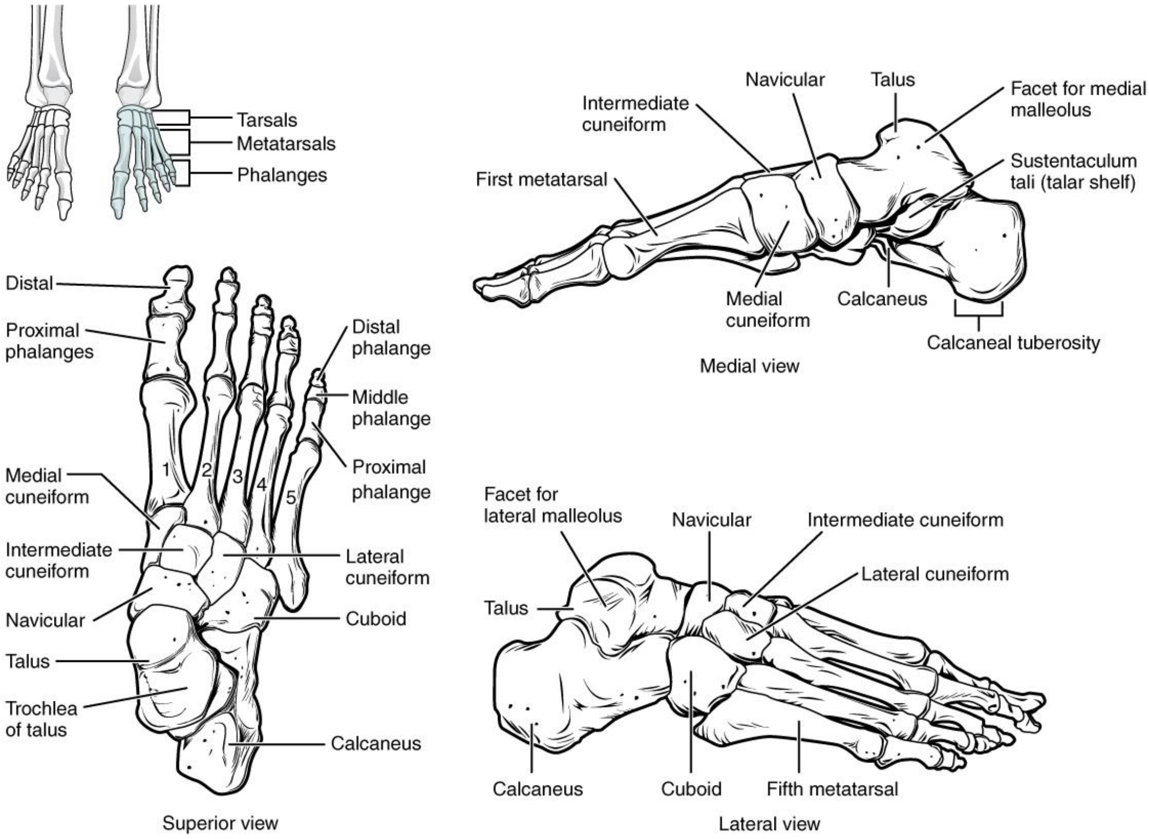


Figure 2.1.1: Bones of the Foot [17]

The rest of the four toes each have three bones with two joints. All phalanges are connected to the metatarsals through five metatarsal phalangeal joints at the ball of the foot. The forefoot and the respective ball of the foot bear half of the body's weight and contribute to the balance standing of human system.

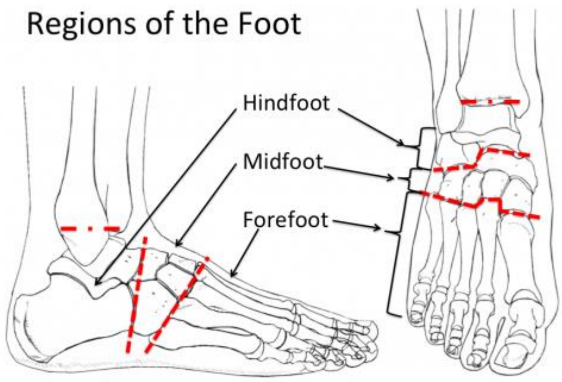


Figure 2.1.2: Different regions of the foot [18]

The mid-foot serves as a shock absorber through five irregularly shaped tarsal bones and forms the foot's arch support. The bones of the mid-foot are connected to the forefoot and the hind-foot by muscles and the plantar fascia (arch ligament).

The hind-foot is made of two bones talus and calcaneus. It connects the mid-foot to talus or ankle via three joints. The top of the talus is connected to the tibia and fibula of the lower leg like a hinge that allows the foot to move up and down. Calcaneus the largest bone in the foot joins the talus to form the subtalar joint. The bottom of the heel bone is cushioned by a layer of fat.

2.2 Why High Heel?

From approximately 1000 BC, women have been wearing high heels footwear to convey social status and fulfil their fashion appeal. In the 1700s, European elegant wavered on heels five inches and higher, utilizing smart sticks to keep them from toppling over. Since 19th century, high heels were very much popular. In the 20th century women started to reveal their demand for more comfortable, flat-soled shoes [19]. But in 20th and 21st century high heels became norm in professional settings and added cultural values for a woman. High heels have even become part of the workplace uniform of women employers [20]. At the same time, heels grew in popularity with the half-world, namely showgirls and artists' models [21]. Sure, they look great but walking in heels causes the back to curve and the chest to push forward, giving ladies that hot come-here position. But for a long time, these high heels wearing could damage their leg to stand on. High heels are considered to pose a dilemma to women as they bring them psychosexual benefits but are detrimental to their health [22].

The Spine Health Institute revealed that 72% of females group wear high heel footwear for some time. 77% of women wear them for special occasions. Among them 50% of women wear them at parties and out of dinner, 33% and 31% of women wear them for dancing and work respectively [23]. On the other hand 49% of female ages 18-24-years-olds, 42% of ages 20-49, and 34% of ages 50 and over wear high heels [24].

2.3 Types of High Heel

The 21st century has familiar with a wide variety and spectrum of fashion, styles, ranging from height and shape of heel to design, materials and color of the footwear. Few popular types and styles of ladies heels are shown below in fig.2.2.1 [25];


Kitten Heels


Pumps


Stilettos


Ankle Strap Heels


Wedge Heels


Wedge Sandals


Cone Heels


Sling Back Heels


Platform Heels


High Heel Sandals


Peep Toe Heels


Cork High Heels

Figure 2.3.1: Different styles of high heel footwear

High Heeled Boots
Ankle Booties
Spool Heels
Mules
Ballroom Dance
Cut Out Heels
Corset Heels
French Heels
Oxfords
Chunky Heels
Comma Heels
Espadrille Heels

Figure 2.3.1: Different styles of high heel footwear

Kitten Heels

People love the style of kitten heels for the comfort / fashion mix. These styles are best for the events like parties or work where you don't need the additional height but will be on your feet for a while.

Pumps

Pumps are typically wider in shape and its height between 2 and 3 inches and also known simply as high heels. These are usually low cut around the front.

Stilettos

It can reach up to 8 inches and the highest among all the high heels. While these heights can create problems walking for many, it's a commendable skill for the stretching impact they have on one's legs.

Ankle Strap Heels

Ankle strap heels are very popular in style at the current time. The height of the heel is not fixed and can vary from style to style, but the one common figure is the strap that circumvents the ankle, making the heels more comfortable and secure to walk in.

Wedge Heels and Sandals

Wedge footwear can be classified into two types; wedge heels and wedge sandals. In wedge heel there is no cavity from the heel to the sole and just like high heel footwear. In wedge sandals there is open upper while the heel as same as wedge heel.

Cone Heels

Cone heels form a shape just like an ice cream cone where wider at the sole of the foot and narrower at the bottom of heel.

Sling Back Heels

The sling back heel has a special kind of strap materials not like the ankle strap heels which goes around the back of the achilles tendon. This gives a more standard look at the same time providing the function of stabilization.

Platform Heels

These styles are available from short to tall. The part of the footwear under the sole is the main element that makes them platform. This thicker part under the sole makes the high heels more secure and comfortable because in that case the difference between the back and front of the foot is lesser.

High Heel Sandals

This is simple types of sandal with varying heights of high heel. It has different types of heel such as stiletto, high, kitten etc. but with a strap upper.

Peep Toe Heels

Fairly a bother, peep toe heels come in a wide variety of shapes and sizes. All they require is for a fly of your colourful toenails to show to be a peep toe!

Cork High Heels

These heels simply made of cork materials which make it softer and cushion able. They can vary in height and style.

High Heeled and Ankle Booties

People wear high heeled or ankle boots in the wintertime when all the trees are brown. But these types of footwear matched well under or over jeans or even with a skirt or dress.

Spool Heels

The concept of spool heels comes from the spool of thread. The heel is thicker at the sole area of the foot, narrow in the middle, and then comes back out at the bottom.

Mules

In Mule heels are comes up high over the top of the foot. It could have an open or closed style and the height of the heel of mule can vary.

Ballroom Dance Shoes

Strappy footwear that usually have a strong support system as enclosed back and ankle strap for getting groove on. They are low enough to be balance and stable but high enough to provide a little vertical lift. These are getting more popular for events like weddings ceremony.

Cut Out Heels

These types of heels have a portion of the upper cut out for getting effect.

Corset Heels

As like as a mule style or a bootie except the two sides of the corset are joint together in a conventional way.

French Heels

Also known as Pompador Heels or Louis Heels, these are same to spool heels except they are short in height but have small curve to waist of the heel.

Oxfords

The standard oxford footwear has an academy look with a flat heel. But lately it found that the heel is still flat at the bottom, but with an excess height than a standard xford.

Chunky Heels

This is a common term for any kind of heel with a square base. They are typically on the flat to medium side, and give more stability than other conventional high heels footwear or stilettos.

Comma Heels

These heels have a shape of comma at the base of heel and then line up with the heel of footwear.

Espadrille Heels

These styles have a textile cloth upper and a plaited fibre sole. This brings something new on the fashion area and is very popular worldwide. Espadrille heels can have a traditional flat, heel or wedge base.

2.4 Types of Materials Used In High Heel

Raw materials for the manufacturing of high heels incorporate wood, plastic, rubber, leather, fabric, paper, and different cements and adhesive, depending on the component materials. Nails, screw nails, and tacks are also used to hold leather or fabric and to set the heels to the shank of the footwear. Fabric, feathers, artificial pearls and stones have all been used to decorate high heels. The main purpose of soles on footwear is to protect the plantar surface of the user's foot, but different parts of it serve different functions. Though the materials and elements used in the heels and soles of footwear production have changed with recent technology, some of the basic parts and materials are still used [26].

Wood

Wood is a very common material used in footwear manufacturing that is also used regularly in today's footwear technology. A shoe maker Jim Barnier has said that the weight of the wooden block is more essential than hardness. Shoe manufacturers used a layer of rubber sheet on the bottom for getting more comfort and to protect the wood.

Cork

Many have used cork in footwear since the fourteenth century. Cork insoles made the footwear both comfortable and protective by moulding it to the wearer's foot. The flexibility of this cork allows the footwear to bend easily and provide natural walking and comfort facility.

Rubber

Natural rubber has been utilized for soles production for many years and is now replaced with a huge variety of synthetic rubber compounds. Carbon rubber from a mixture of synthetic rubber and carbon, solid rubber from a mixture of natural and synthetic rubber, vulcanized rubber from the mixture of natural and crump rubber with sulphur and gum rubber from a combination of natural and synthetic rubber that provides good traction, but less durability etc. are the main forms of rubber used in sole.

Leather

Soft, thin leather or thick, rigid buffalo vegetable tanned leathers are commonly used as insoles and soles of footwear. Occasionally it has thin rubber additions to leather-soled footwear to help protect the leather and increase traction. A combination of leather and rubber is also used in footwear production.

2.5 Effects of High Heeled Footwear

While wearing high heel women's body try to compensate for the bizarre balance due to forward bending or flexing the hips and spine. The back muscles, calf and hip become tense while maintain balance standing or walking with high heel. With prolonged wearing, these creates for extra muscle fatigue and strain as well as also cause the lower leg muscles to cramp and lump. That can lead to long-term complication for women's feet. Previous study show that at the present time about 43 million Americans experienced painful foot defects—such as bunions, callouses, and hammertoes—and majority of them are the consumers of high heeled footwear [19].

Side effects that commonly found in high heel consumers are;

Hallux valgus

Hallux valgus deformation was believed to be caused by an irritated flexor hallucis muscle at the first metatarsophalangeal joint [9], particularly when external tensions insist the hallux to abduct and thus cause hallux valgus deformity. According to a survey [6], 71% of high heel wearers experienced with hallux valgus deformation.

Hammer toe

Abnormal extrinsic forces and muscle imbalance lead to the development of a hammer-toe deformity. A high heel footwear with a narrow shape and short in size forces the metatarso-phalangeal joint into hyperextension and the proximal inter-phalangeal joint into flexion, which can cause stretching and failure of the plantar surface [27].

Sore Calves

Sore calf muscles are one kind of defects from pointed heels. It can also prompt to bulging veins, which look shocking as well as extremely painful too [28].

Foot Pain

After a time with uncomfortable high heel footwear on the feet, consumers are most probably to suffer from a foot ache. A sharp pain in the sole, toes, arch or heel can be experienced by the users [29].

Knee Pain

The awkward arc of the leg while wearing high heels exerts too much stress on the knee joint. It often leads to causes of osteoarthritis in high heel consumers.

Lower Back Pain

An unequal distribution of weight caused by high heel may trigger inflammation, soreness and pain in the lower back [30].

Ankle Sprains

Some potential party poopers like potholes, bumps and cobblestones waiting for the users to slip and sprain their ankle. Aside from the lower leg sprain, a fall like this can also prompt to broken ankles, wounded elbows and knees [31].

Awkward Spinal Curve

High heel footwear makes the lower back arch shift away more than usual. In fact, there is a direct proportional relationship between heel height and the degree of arch in the back of users. The awkward arch can create awful injury in the upper and lower back sides [32].

Constricts Blood Vessels

In high heel the footwear shape restraints the foot into a situation that undoubtedly is not natural and is definitely not comfortable. The stress and strain on the foot can cause a compressed blood flow. Sometimes in extreme cases, it might cause the veins break [33].

Crooked Feet

Hammer toe/Crooked Feet is one of the most serious side effects of high heels on feet. The abnormal position of the foot, the strain on the calves, veins and back result in a defects of the foot, called hammer toe [34].

Weakens Ligaments

High heels debilitate the ligaments.

2.6 Human Factors and Ergonomics of High Heel

Lumbar Lordosis, Anterior Pelvic Tilt, and Posture

No significant differences were found in average lumbar arc or anterior pelvic tilt for several heel height conditions [35, 36]. The relative positions between body sections changes by wearing high-heeled footwear. At a time of standing with high heeled footwear ankle plantar-flexion increases [35, 36] and the knee is kind of hyperextended [36].

Joint Angles

The most significant differences are noticed in the ankle joint angle for heel height. While walking at a normal self-supported speed in the high-heeled gait, the knee is flexed more at the heel contact and in the first half of the stance phase compared to the barefoot or flat-heeled gait [37, 38]. Many studies reports no significant differences in hip joint angle between heel height conditions [35, 36] during walking on plane surface. But during the stance phase the tibia is more internally rotated in the high-heeled gait than in the flat-heeled gait [38]. In the movement on a regular plane, both the foot eversion (pronation) and foot abduction is lesser in the high-heeled gait [36, 39, 40].

Foot Morphology

With increase of heel height, instep length becomes shorter. The cross sectional view of the shape of mid-foot become laterally rotated and thus narrower, higher, and less flat with the increasing heel height [41]. A shorter length of instep or medial arch when wearing high-heeled footwear is also observed by radiographic assessments [42].

Time Factors and Distance Factors

Some previous studies showed that walking at a self-supported speed, the walking is slower and the stride length is shorter in the high-heel condition than in the flat heel or barefoot conditions [37, 38, 43]. But no difference is noticed in the step width between the high-heeled gait and the lower-heeled gait or between the high-heeled gait and the barefoot [39].

Weight Distribution

When the foot is plantar-flexed, the separation from the heel to the ankle joint projected on the floor increases, while the separation from the metatarso-phalangeal joint to the ankle joint projected on the floor decreases [44]. Therefore, the stress at metatarso-phalangeal joint becomes larger, and the pressure at the heel becomes smaller.

Ground Reaction Force

Walking at a self-supported speed on over ground with wearing high heel, no significant difference was observed in the antero-posterior and lateral parameters of the ground reaction force [36, 37, 45] but both active peaks of the vertical components of ground reaction forces are larger. The impact force at the heel contact is also reported to be high in high heeled footwear [45, 46].

Muscle Activities

During walking, the heel height disturbs the functions of the foot and the leg muscles, but the thigh and the trunk muscles are not so much affected. The level and/or duration of activities increased in high-heeled footwear's in seven muscles (flexor digitorum brevis, abductor digiti minimi, abductor pollicis, peroneus longus, tibialis anterior, gastrocnemius medialis, and rectus femoris [47].

Motion and Force

While walking in high-heeled footwear, the ankle joint is always more plantar-flexed than wearing flat-heeled footwear. The flexion of knee and hip joints raises due to the larger plantar-flexion of the ankle joints to compensate for the forward movement of the centre of mass [37, 40]. The activity of the tibialis anterior muscles increases in high-heeled footwear but the concentric plantar-flexor power is smaller than that in the lower-heeled condition, and thus shock absorption by the ankle joint is limited [47].

Stability

In high heeled footwear, the static balance, range of maximal antero-posterior balance, and coordinated stability all the performance were worse comparing with the barefoot or low-heeled condition [48].

Plantar Pressure Distribution

In high-heeled footwear the center of plantar pressure moves forward and redistributes plantar pressure, while the stress to the forefoot, particularly the pressure over the medial longitudinal arch and forefoot latitudinal arch, is substantially increased [49]. John et al.

found that the contact area of forefoot with the footplates decreased as the heel was raised and there was a shipment of load towards the medial forefoot region a resultant increase in pressure [50]. When heel heigh increased, the center of pressure moved from the mid-foot position to the forefoot position, the contact area is decreased by 26% from 0 to 10.2 cm heel and the internal stress of foot bones increased [7]. Pressure beneath the forefoot was found to rise significantly with increasing heel height. With the heel elevation the peak pressure shifted toward the first metatarsal and the hallux [51]. The peak pressure and shear stress shifted from the lateral to the medial forefoot as the heel height increased from 3 to 7 cm. The peak shear has five times greater influence than peak pressure in that elevation and could be a cause of hallux deformity [8]. According to Caroline et al. plantar pressure reduced under the heel and in the mid-foot with high heels and caused an increase in peak pressures of 30% in the central forefoot (metatarsals 2–4), whereas in the medial forefoot (metatarsal 1) 34% in comparison with low heels [10].

Foot-bed cushioning

softness, mushiness, reducing jarring motion, shock absorption, comfort, support, the sinking feeling, protection, stability, deceleration etc. are the indicators of cushion [52]. Materials with low stiffness can give adequate conformance between foot and foot-bed. According to biomechanics and ergonomics literature, injury has been connected to shock absorption while hardness and stiffness have been connected to discomfort [52]. The human body has the ability to detect harming movements as discomfort or pain. Poor cushioning ratings are a good predictor of discomfort and pain in feet [53].

Comfort

The comfort rating decreases with the elevation of heel height, [45, 46]. The sensory evaluation scale like visual analog scale or a Borg scale was used to evaluate the perception of comfort through quantifying the perceived intensity of stimulation [45, 54]. However, since the assessment of comfort is subjective, it may be vary from one to another. The features of foot-bed shape (wedge angle and heel sheet length) and perception of comfort is related to each other. The rating of comfort was higher when the heel sheet length was selected based on the individual's foot dimension rather than a constant value [55]. The total contact insert also affects comfort ratings and become higher when all three values (peak foot pressure in the medial forefoot, impact pressure, and first peak of the vertical ground reaction forces) are smaller [45].

2.7 Techniques of Plantar Pressure Measurement

Investigation and interest on the distribution of foot plantar pressure has been continued for more than 150 years. An early investigation of foot-to-ground interaction was made by letting participants stand on and walk across plaster of Paris and clay [56]. Measurements of pressure distribution have widely been utilized for basic research to evaluate the mechanical behaviour of the foot in static and dynamic loading situations. Furthermore, the pressure distribution instrumentation was studied to assess the effect of body weight and obesity on foot function and pain [57]. In footwear, plantar pressure measurements are essential to assess the effect of shoe construction and design on foot loading. Most of the pressure distribution study related with footwear has a clinical background with an emphasis on the lowering of high pressures in diabetic and rheumatoid feet.

Study of plantar pressure is getting very popular in clinical, sports, and design of footwear and rehabilitation studies. This strategy can help to identify and analyze muscular defects, postural anomalies, pathologies, design of footwear, geometry of outsole and evaluate gait and standing posture ([58-61]. There are some technology have developed to monitor foot plantar pressure distribution but most of those devices are high cost and not available to the researchers from lower developed country. Self-constructed plantar pressure monitoring systems have developed by many researchers. Satio et al. developed a prototype device to monitor in-shoe plantar pressure during walking [62]. Crea *et al.* introduced a pressure sensitive insole for the study of plantar pressure distribution [63]. Motha et al. demonstrated an instrumental rubber insole printed with embedded pressure sensor for detection and investigation of plantar pressure [64]. Tan et al. designed and developed a plantar pressure measuring smart insole [65]. Varoto et al. described the development and application of insole sensor to monitor foot plantar pressure [66]. Recent time, some commercial techniques stand out in the analysis of plantar pressure, body motion and for gait characterization. Baropodometric Platforms and Sensorized Insoles (Sensor Medica, Italy) are commercially available for the evaluation of foot plantar pressure, and patient's posture during walking and standing. The medilogic WLAN insole (Medilogic, Germany) aids in orthopaedic footwear making. The Pedar System (Novel, Germany) is a technique of monitoring dynamic pressure distribution between the foot and footwear. The F-Scan System (Tekscan, USA) provides flexible tactile resistive insole sensors to get dynamic information about foot function and gait. But most of these systems are costly and not commercially available in all countries within the research budget.

Force sensitive resistor (FSR) is a low cost and frequently used for pressure measurement. Yun et al. applied FSR to evaluate the comfort of driver seat [67]. Smith et al. used FSR to improve walking in the child with cerebral palsy through triggering electrical stimulation [68]. Pawin et al. showed human's abnormal gait can be calculated by using the signal from low cost FSR through installed in the sole of a shoe [69]. Sayed et al. used FSR for the recognition of surface texture [70].

Pressure is calculated as force divided by the contact area on which this force acts. It is expressed in units of kPa (100 kPa = 10 N/cm2). Plantar pressure measuring instruments are needed to calculate pressures and pressure distributions. All plantar pressure measurement technologies are based on the registration of strain of materials [5].

Transducer Technologies

Depending on the quality and type of transducer, forces can create electrical charges, modify the resistance, cause a change in capacitance, or influence inductance. The characteristics of transducers for biomechanical applications can differ by the criteria and quality of sensors. Plantar pressure measurements during sitting, running with footwear, and laying on a bed demand a soft and pliable transducer matrix that will adapt to the shape of the human anatomy. Based on different technologies, several pressure distribution systems like Novel, Tekscan etc. are sold today. Most of them are used for the analysis of the foot-to-ground interaction as pressure platforms or as insoles for in-shoe measurements.

Resistive Sensors

The electrical resistance changes in resistive transducers under compression or tension of the transducer. Typically, two thin and flexible polyester sheets with electrically conductive electrodes are separated by a semi-conductive ink layer between the electrical contacts. With increasing pressure, the conducting particles are pressed closer together, increasing the surface contact between the conducting particles and thus lowering the electrical resistance.

FSR

Force resistive sensors (FSR) are simple and low cost used to detect physical pressure, squeezing and weight. FSRs are basically a resistor that changes its resistive value (in ohms Ω) depending on how much it’s pressed. These sensors are fairly low cost, and easy to use but they are rarely accurate. They also vary some from sensor to sensor perhaps 10%. So basically when you use FSRs you should only expect to get ranges of response. FSR 406 is a sensor of interlink electronics with a sensing area of 39.6 square millimetre.

Capacitive Sensors

Electrical capacitors typically composed of two conducting plates or foils in parallel to each other separating with an insulating dielectric material. In a capacitive force transducer, the capacitance changes as a function of distance between the two conducting surfaces and a change in dielectric material properties. Application of load on such a transducer causes a change in the distance between the surfaces of two conducting capacitor as well as a change in the dielectric constant between the electrodes of the compressed material.

Piezoelectric Sensors

Quartz often used as sensor material in high precision force transducers. But a very lower amount of electrical charges is generated from the surface of the quartz. Hence high performance charge amplifiers need to be used for electronic processing which is very costly. Piezoceramic materials also generate electrical charges with approximately 100 times higher when they are compressed as compared to the quartz. This high charge generation permits the use of low cost charge amplifiers and thus allows the construction of low cost pressure measurement devices.

Table 2.7.1: Plantar Pressure Parameters and their definition's [5]

Parameters	**Definition**
Peak Pressure	Maximum plantar pressure of a pixel or within a region
Mean Pressure	Mean plantar pressure of a pixel or all sensors within a region
Centre of pressure	Point at which all pressures are centred
Contact time	Time between heel strike and toe-off
Total contact area	Surface of plantar area that has contact with the floor

2.8 Studies on Load Redistribution

The peak pressure in the rear-foot can be reduced by the heel cup and the insertion of total contact and in the medial forefoot it can be reduced by the impact force, and the arch pad and the total contact [46]. Insertion of thick soft foam could reduce pick pressure by 26%, impact force by 27% and force time integral by 20% when compared to the condition without insert in a high heeled shoe [12]. Luximon et al. used three types of pad like bio gel, polyurethane and EVA, among them polyurethane pad showed the lowest peak pressure on the forefoot and reduced the peak pressure by 35.54% [13]. Paton et al. decreased pick pressure and pressure-time integral by using 7mm semi-compressed felt plantar cover padding, with a U shape cutout to the second metatarsal head by a mean of 25% and 29% respectively [14]. Felt padding of 7mm produces a greater reduction in force than 5mm felt padding compared to a control of no felt padding [15]. Hayda et al. study different pad types with at different pad positioning and found each pad type and position caused a variable effect upon plantar pressure [71]. Metatarsal pads reduce pain and improve the American Orthopedic foot & ankle society score to 24.2 points in all patients, among women 19 points, and among men 29 points [11].

CHAPTER III

Methodology

3.1 Materials selection and specification

Four different types of materials were collected from the local market and used in the experiment for metatarsal cup formulation. As past study indicate that the foot plantar pressure could be influenced by material stiffness [12, 72, 73] softer to harder materials including conventional mode (light hard rubber covered with soft cushioned insole), medium soft EVA (MSEVA) and very soft EPDM (VSEPDM) Neoprene Sponge pads were chosen for the metatarsal cup formulation.

Table 3.1.1: Materials specification

Items	*Tensile Strength, N/cm2	*Young's Modula's, N/cm2	Density Kg/m^3	**Hardness H°
Hard Rubber	15.18	28.49	1363	Shore-A 58
Medium Soft Rubber	5.0	4.37	1059	Shore-A 28
Medium soft EVA	7.23	4.41	1095	Shore-A 33
Very Soft EPDM Neoprene Sponge	1.78	0.90	142	Shore-O 39

*Tensile Tester: SATRA TM29:1992;
**Durometer: SATRA TM205;

i) Conventional high heeled base materials

Light hard rubber with shore A 58° hardness was selected as the base soling materials of conventional high heel with density of 1363kg/m3. The Young's modulus and tensile strength was 28.49 N/cm^2 and 15.18 N/cm^2 respectively. Soft rubber is flexible and has cushioning abilities and commonly used as an insole material on the top of high heeled footwear. The Young's modulus, tensile strength and Shore A hardness of this cushion pad was 4.37 N/cm2, 5.0 N/cm2, and 28° respectively.

ii) Medium Soft EVA

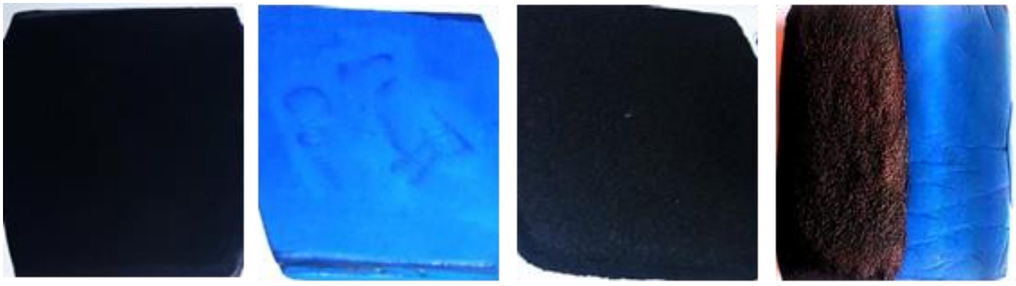
MSEVA is a low density and commonly used in-soling material due to its ability to cushion and occasionally used as sole material. The density and hardness of this material was 1095kg/m3 and 33° (shore A) respectively. The Young's modulus was 4.41 N/cm^2 and the tensile strength was 7.23 N/cm^2.

iii) Very soft EPDM Neoprene Sponge

EPDM Neoprene Sponge is extra soft, highly stretchable and its hardness was 39° shore O. It can absorb shock to a large extent, and efficiently relieve pressure and shear force. The corresponding Young's modulus and tensile strength of this material was 0.90 N/cm^2 and 1.78 N/cm^2. The material property of all the above materials was tested with the help of ISO and SATRA standard.

3.2 Making of a joint padded cup

JPMC was designed and made up from two different types of compressed and soft materials one of MSEVA and the other is VSEPDM neoprene sponge. The two different parts of materials were attached with adhesive. A blank hole at the metatarsal basement area of forefoot was made and assembled the developed padded cup on this site. At the same way three different types of metatarsal cup was prepared to compare with the developed one. One of those is a representative of the conventional system made with light hard rubber covering with soft cushion as insole material. Another two cups for MSEVA and VSEPDM sponge was made separately. All the pads of metatarsal cup had the same size, thickness and shape, but different materials (Figure 3.1). The thicknesses of the metatarsal pads were around 18mm.



(a) (b) (c) (d)

Figure 3.2.1: Metatarsal pad made of (a) Conventional materials (hard rubber covering with soft rubber/cushion insole); (b) medium soft EVA (MSEVA); (c) Very Soft EPDM (VSEPDM) Neoprene Sponge; and (d) Joint padded metatarsal cup (JPMC) from very soft EPDM and medium soft EVA

3.3 Making of high heeled female footwear

Three pairs of high-heel (English size 6-8) with a height of 4.5 cm at forefoot and 12 cm at hind foot area was prepared (Figure 3.2). All of the footwear pairs were custom designed and prepared manually. The metatarsal pads were then inserted into the cavity under the metatarsal region of the forefoot (Figure 3.5), which gave a similar measure of zone for the forefoot of every member.

(a) (b)

Figure 3.3.1: Prototype Footwear: (a) top view; (b) outside view

3.4 Participants

Three different numbers of participants were selected for the study.

Category-1

Ten adult females with normal feet were selected to participate in the measurement of plantar pressure distribution. The average age of this group of participants were 20.7 years old with a minimum age of 17 and a maximum of 23. The range of body weight was 48kg to 53kg with an average of 50.6kg. In addition all the participants were right foot dominant and their shoe sizes varies from 6 to 8 English points.

Category-2

Three females of around twenty years old of normal feet with 51.6 kg mean weight and 159.8 cm mean height were chosen for radiographic analysis. The shoe sizes of the participants were 6 and 8 U.K.

Category-3

Finally twenty female participants experienced in wearing high-heeled footwear volunteered to take part in the survey for hypothesis test. The average age of those participants were 21.8 years with a range of 15 to 34 years old. The average height of the consumers was 155cm.

3.5 Experimental Setup for Plantar Pressure

A system was developed to measure the plantar pressure in this experiment. Where a Force Sensitive Resistor (FSR 406) [74] pad with 39.6mm square active region (Figure 3.5.1-b) was connected through the Arduino and LCD display, and inserted into the footwear (Figure 3.5.1-a). The instrumentation associated with the switching circuit, and performs analog to digital conversion of voltage and resistance into pressure.

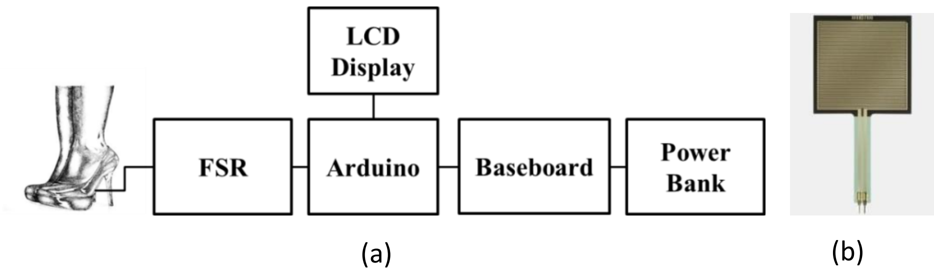


Figure 3.5.1: (a) Block diagram of the system; (b) FSR; with 39.6 mm active areas;

The switching circuit, including modified voltage dividers, converts resistance into voltage. Furthermore, the microcontroller provides serial data to data acquisition module that sends it to LCD display as pressure N/cm^2.

3.6 Load vs. pressure tests for FSR verification

The sensor was selected for the experiment after being tested with known weights for the characteristic calibrated curve (Figure 3.6.1). The applied force range was from 0 to 60 kg. The calibrated outcomes with linearity factors of almost one and coefficients of assurance of R2>0.99 demonstrate that the estimation framework is a dependable technique to detect foot plantar pressure.

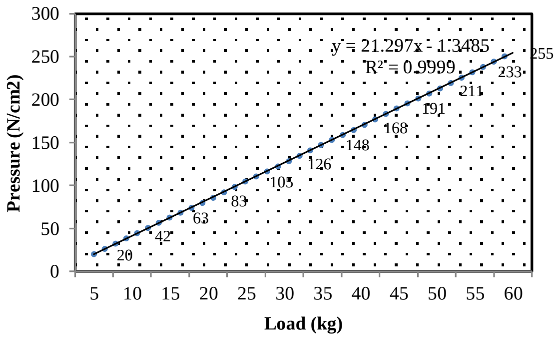


Figure 3.6.1: Calibration curve of load vs. pressure

3.7 Data Acquisition Module

FSR is a sensor that senses the pressure applied on it. It is used to measure the physical pressure and weight. It converts the pressure into voltage and then detects the pressure.

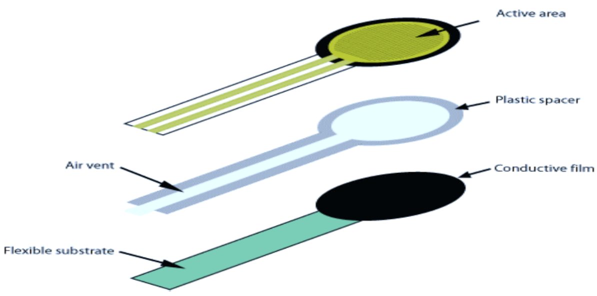


Figure 3.7.1: Layers of Force Sensitive Resistor (FSR) [75]

The FSR consists of 2 layers as shown in Fig. 3.7.1, named sensing film and conductive polymer. The electrically conductive and non-conductive particles of sub-micrometer sizes form the sensing film. The conductive polymer changes the resistance in accordance with the applied force on its surface. Two surfaces are separated by a plastic spacer.

One terminal of the FSR is connected to the Vcc and the other is grounded through a Pull-Down resistor, RPDR. RFSR is a variable FSR resistor and RPDR is a fixed resistor. Analog output voltage, Vo is collected from the combined point of RFSR and RPDR then used as the input voltage at the analog input point.

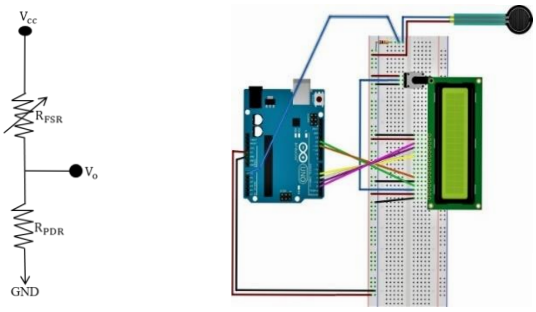


Figure 3.7.2: Wiring diagram of FSR and LCD monitor with Arduino

Liquid Crystal Display (LCD) has 12 pins among which 6 pins are digital pin. 4 Digital pins (pin D4 to pin D7) of LCD were connected with the digital pins (pin 4 to pin 7) of Arduino. Then the Register Select (RS) pin (pin 4) of the LCD was connected to the Arduino at pin number 1 and the Enable (EN) pin of the LCD was connected to the pin number 2 of the Arduino. Mode of the R/W pin was selected as write mode to write and send commands and data to the LCD.

The conducting resistance between the sensing film and the conductive polymer is responsible for the current conduction. Active element dots are connected with the conductive polymer when force is applied on the FSR surface which created more effective area for current conduction. As the more force is applied, the more contact path is created which decreases the resistance of the FSR. Output analog voltage can be represented as,

$$V_o = \frac{R_{PDR}}{R_{PDR} + R_{FSR}} V_{cc} \quad (1)$$

Analog output voltage follows the voltage divider rules. When forces were applied on FSR surface, the resistance RFSR was decreased. According to the voltage divider rules, voltage across the Pull-Down resistance, RPDR was increased. So the analog output voltage was increased with the increasing pressure.

It scaled the changing voltage into Newton. To do this conversion, the system was calibrated using some known weights.

3.8 Foot plantar pressure measurement for the validation of the device

The high-heel female footwear's used in this study were custom made with similar construction and sole materials (Fig. 3.8.1). The height of the heel was the only difference among this footwear's and specified as: flat heel (1 cm), medium heel (5 cm), and high heel (9 cm).

Figure 3.8.1: High heel with three different heights; from left to right, (a) flat heel, (b) medium high heel, and (c) high heel

Eight normal female participants were selected for the test and data collection. The average age, height and weight of the group of participants were 21 years, 159 cm and 56 kg respectively. All participants are habituated with different types of heels.

The participants were asked to walk for 5 min with their regular pace. After that the FSR sensor of the system was placed beneath the foot plantar surface and on the medial forefoot area (below 1st and 2nd metatarsal head) between foot and insole. To make the placement of FSR in a similar way with respect to the foot bottom surface and metatarsal region, a frame was made with a pattern paper. During standing, data of plantar pressure was monitored and presented in Table 3.8.1. In the same way, the process was completed for the rest of high heel footwear with all participants.

Statistical data analysis of forefoot peak plantar pressure was conducted with a statistical tool. Experimental data was compared and analyzed with some previous studies that have been done on plantar pressure at different heel height.

Table 3.8.1. peak plantar pressure on medial forefoot of three different heel heights

Condition	n	Mean ± SD (N/cm^2)
1 cm height	8	5.38 ± 1.59
5 cm height	8	9.12 ± 2.10
9 cm height	8	11.0± 2.50

The calibration curve for the verification of working ability was plotted as load versus pressure in Fig. 6. The coefficient of the determination indicated that the device was working properly. During experiment as the heel height was increased from flat to high heel, the load increased gradually. The plantar pressure was increased to 69.7% when shifted from flat to medium heel and it was raised 104% from flat to high heel footwear. With the comparison of medium to high heel it was raised to 20.5%.

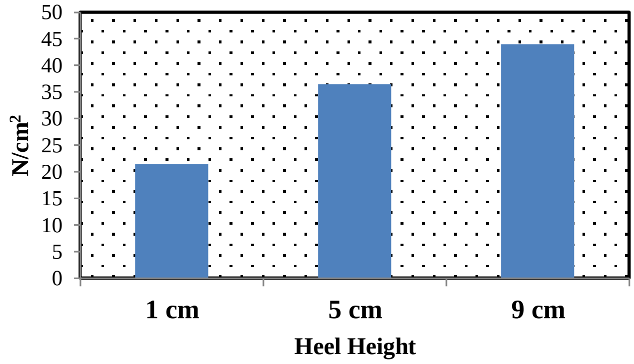


Figure 3.8.2: Foot plantar pressure; from left to right flat heel (1cm), medium heel (5cm), and high heel (9cm)

The obtained results were compared with the previous study to the measured plantar pressure from Cong et al. [8], Yung-Hui et al. [46] and Gu et al. [76] and displayed in Figure 3.8.3.

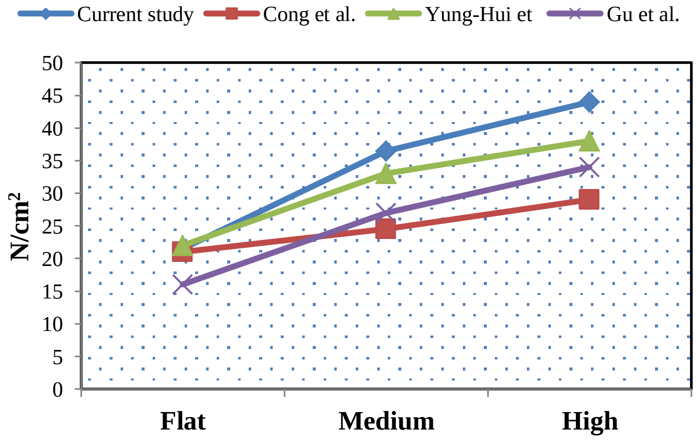


Figure 3.8.3: Comparison of experimental data with previous studies from; (a) Cong et al., (b) Yung-Hui et al., (c) Gu et al.

Cong et al. [8] studied on in shoe triaxial stresses based on different heel heights. They used three different heights (3, 5 and 7 cm) of ladies heel footwear and measured foot plantar pressure of ten female participants using force sensing transducer. The plantar force under 1st and 2nd metatarsal head increased gradually with heel height and showed 17% when shifted low heel to medium, 18.3% when medium to high heel, and 38% when shifted from low heel to high heel.

Yung-Hui et al. [46] investigated the plantar pressure on foot inserts when heel height increased from flat (1 cm), medium (5.1 cm), to high heel (7.6 cm). They used pedar plantar pressure measurement system (Novel, Germany) to monitor pressure distribution and found a gradual change with heel height as 50% when shifted from flat to medium, 72% when compared from flat to high heel and it was 15% when shifted from medium to high heel.

Gu et al. applied twelve female participants to observe foot loading on outsole area while walking in high heeled shoe. Heel with three different heights flat (0 cm), medium (4.5 cm), and high (8.5 cm) were used for the investigation and found remarkable change when shifted from flat to medium (40%), medium to high (26%), and flat to high (112.5%). They obtained their data through the novel embed system.

The measured values from the present study were compared and analyzed through statistical tool and their respective relativity coefficients were obtained from the comparison and it was r21=0.93, r22=0.99, and r23=0.99 respectively. The graph r1, r2, and r3 were plotted in Fig. 3.8.4a, 3.8.4b and 3.8.4c for both the experimental and review paper. The relativity of coefficient values demonstrates that there is a good connection of the developed system with referenced studies.

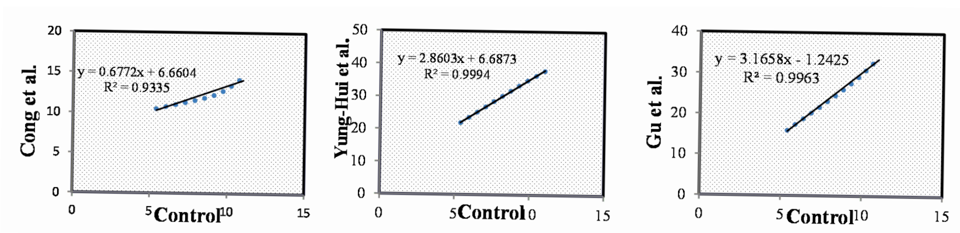


Figure 3.8.4: Relativity coefficient graph of comparative data with previous study (a) Cong et al., (b) Yung-Hui et al., (c) Gu et al.;

These results indicated that the system of plantar pressure measurement with low cost FSR is possible with acceptable accuracy. Above calibration and verification of performance by the participants indicated that the system or device was effective to monitor the static foot plantar pressure. In the future, Internet of Things (IoT) can be applied to record and observe the data in dynamic condition smoothly and remotely.

3.9 Plantar pressure measurement process

The selected subjects were capable of walking normally asked to wear the developed footwear tied with laces for 10 minutes. Then the data was measured and recorded for the five different portion of female foot plantar surface (Figure 3.9.1) such as central heel (CH), medial forefoot (MF), central forefoot (CF), lateral forefoot (LF) and hallux (H). At the same way, the experiments with different metatarsal padded configurations were conducted consequently to measure the plantar pressures under static condition of participants. All the data was taken by ensuring the placement of sensor to the desired area of foot plantar surface using a template. A standard posing and body balancing was also maintained through the analysis.

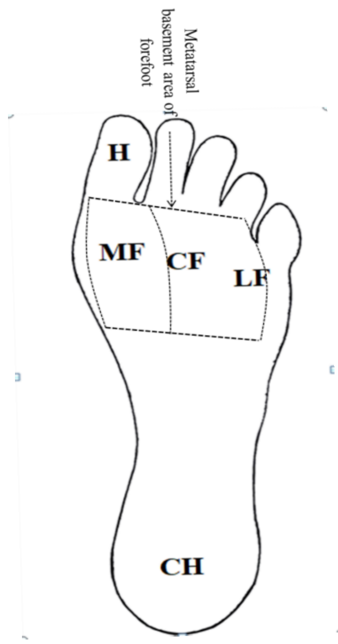


Figure 3.9.1: Schematic foot plantar shape of the subject with anatomical locales of interest; H: Hallux; MF: Medial Forefoot (first metatarsal head); CM: Central Forefoot (second to fourth metatarsal head); LM: Lateral Forefoot (fifth metatarsal head); CH: Central Heel

Figure 3.9.2: Measurement of female foot plantar pressure

3.10 Experimental Setup for Radiographic Test

Three female participants consented to take part in the radiographic experiment. Antero-posterior view of wearing high-heeled against different types of metatarsal pads as well as barefoot condition was taken through radiograph according to Table 3.10.1. All radiographs were taken on the same x-ray machine (1000mA HITACHI) in one centre. A custom-made paper template was developed to fix the position of the foot and leg relative to the X-ray camera and plate in a standardize way. A predefined sketch of foot was drawn and blanked onto the template paper. This custom aimed to standardize foot placement on the repeated radiographs of the different interventions.

Table 3.10.1: Experimental guide for radiographic test

Position	**Footwear set up**	
	Left Foot	**Right foot**
Anteroposterior view of barefoot	Barefoot	Barefoot
Anteroposterior view of the female foot wearing high-heel	Conventional	Metatarsal cup with control mode
	Conventional	Metatarsal cup with VSEPDM Neoprene sponge
	Conventional	Joint padded metatarsal cup

Four antero-posterior (AP) radiographs of the right foot were taken consequently in: (i) barefoot condition, (ii) high heel of conventional mode, (iii) high heel with VSEPDM neoprene sponge cup, as well as (iv) high heeled footwear with JPMC. Selected participants were positioned in standing with fully weight bearing on the template.

CHAPTER IV

Results and Discussion

4.1 Data and statistical analysis

4.1.1 Plantar pressure distribution

In shoe plantar pressures were measured using FSR at LF, CF, MF, hallux and CH position. As all of the participants are right footed, all of the data for plantar pressure measurements were taken from the right foot and were recorded in Table 4.1.1 and their mean values were displayed in Table 4.1.2.

Table 4.1.1: Pressure distribution at different position of female foot plantar surface

Materials	Heel (N/cm2)	Medial forefoot (1st Finger) (N/cm2)	Central forefoot (2-4 finger) (N/cm2)	Lateral forefoot (5th finger) (N/cm2)	Hallux (N/cm 2)
Barefoot	**17**	**1**	**11**	**2**	**0**
	26	**5**	**17**	**6**	**1**
	17	**2**	**12**	**7**	**0**
	26	**7**	**18**	**10**	**1**
	15	**2**	**11**	**3**	**0**
	24	**6**	**18**	**7**	**1**
	16	**2**	**11**	**2**	**0**
	25	**7**	**17**	**7**	**1**
	25	**5**	**17**	**8**	**1**
	15	**2**	**12**	**3**	**0**
Control	**7**	**12**	**7**	**1**	**2**
	12	**18**	**11**	**2**	**6**
	10	**11**	**6**	**1**	**2**
	16	**17**	**11**	**1**	**5**
	7	**13**	**7**	**2**	**1**
	12	**18**	**12**	**1**	**5**
	8	**13**	**9**	**1**	**1**
	12	**18**	**11**	**2**	**5**
	17	**17**	**10**	**1**	**5**
	10	**12**	**7**	**1**	**2**
Medium soft Eva	**8**	**8**	**7**	**2**	**1**
	16	**13**	**13**	**5**	**3**
	8	**8**	**8**	**1**	**1**
	16	**13**	**13**	**3**	**5**
	8	**8**	**7**	**0**	**0**
	15	**16**	**13**	**2**	**2**
	9	**8**	**7**	**0**	**1**
	16	**13**	**12**	**3**	**3**
	15	**10**	**12**	**3**	**5**

	7	**7**	**7**	**1**	**2**
Very soft	**7**	**5**	**8**	**1**	**0**
EPDM	**12**	**10**	**13**	**3**	**3**
Neoprene	**7**	**6**	**7**	**1**	**0**
sponge	**12**	**11**	**13**	**3**	**5**
	8	**7**	**6**	**0**	**0**
	12	**12**	**11**	**2**	**3**
	8	**6**	**6**	**0**	**0**
	13	**11**	**10**	**3**	**3**
	13	**11**	**12**	**3**	**6**
	10	**5**	**7**	**0**	**2**
Joint	**7**	**7**	**7**	**2**	**0**
Padded	**13**	**11**	**12**	**4**	**3**
Cup	**6**	**8**	**7**	**2**	**0**
	12	**12**	**12**	**5**	**2**
	7	**7**	**8**	**2**	**0**
	12	**12**	**12**	**5**	**2**
	7	**6**	**8**	**1**	**0**
	12	**10**	**11**	**4**	**2**
	13	**11**	**13**	**3**	**3**
	10	**8**	**8**	**2**	**1**

Table 4.1.2: Mean peak plantar pressures on forefoot and heel areas with different padding conditions

Items	NC	MF N/cm2	CF N/cm2	LF N/cm2	Hallux N/cm2	Heel N/cm2
		Mean ± Std.	Mean ± Std.	Mean ± Std.	Mean ± Std.	Mean ± Std.
Barefoot	10	3.9±2.37	14.4±3.27	5.5±2.81	0.5±0.52	20.6±4.79
Control	10	14.9±2.90	9.1±2.17	1.3±0.50	3.4±2.00	11.1±3.63
MSEVA	10	10.4±3.03	9.9±2.86	2.0±1.61	2.3±1.80	11.8±3.90
VSEPDM	10	8.4±2.72	9.3±2.87	1.6±1.30	2.2±2.33	10.2±2.63
JPMC	10	9.2±2.34	9.8±2.45	3.0±1.45	1.3±1.32	9.9±3.01

4.1.2 Assessment of foot morphology

The hallux valgus angle is the extent of hallux valgus deformity which is determined by measuring the angle between the axis of the proximal phalanx and the first metatarsal. The normal value of this angle is less than 15°. Inter-metatarsal angles were also recorded by measuring the angle between the first and second metatarsals (Figure 4.1.1). The normal value is less than 9 degrees [77].

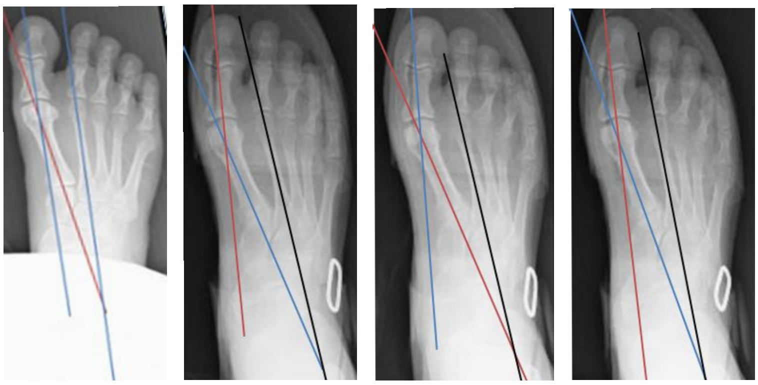


Figure 4.1.1: Anteroposterior view of female foot with (a) Barefoot standing position; (b) Conventional metatarsal base; (c) Metatarsal cup of VSEPDM Neoprene sponge; and (d) JPMC

All of the angles were measured using circular protractor 360° tool for angular displacement. The measurements of those angles were recorded from all participants and shown in table 4.1.3.

Table 4.1.3: Angular displacement of Hallux valgus angle (HVA) and Inter-Metatarsal angle (IMA)

Value	Participants	Barefoot	Conventional	VSEPDM	JPMC
	P-1	3.1°	7.5°	6°	5°
HVA	P-2	9°	18°	19°	14°
	P-3	16°	26°	23°	21°
	Mean	9.4°	17.2°	16°	13.3°
	P-1	5.8°	6.4°	7.5°	7°
IMA	P-2	9.5°	10°	10°	9°
	P-3	11.5°	14°	13.5°	12°
	Mean	8.3°	10.1°	10.3°	9.3°

4.1.3 Consumer Survey

The survey was collected the responses of 20 female consumers of high heeled footwear. The conventional metatarsal base was inserted in the left foot and the developed JPMC in the right foot. The participants were given sets of time for assessment of comfort level at the metatarsal region. They had provided their opinion based on a comfort scale rating from 0 to 10 where 0 represents mostly uncomfortable and 10 represents mostly comfortable footwear. The two-factor ANOVA with replication of the data was carried out and shown in table 4.5.

They rated their total comfort from 0 to 10, using the scale below in table 4.4.

Table 4.1.4: Survey at the starting time of use/after 10min/20min/30min of walking

The amount of total comfort you are experiencing right now:	Rating	The amount of total comfort you are experiencing right now:	Rating
Highest comfort possible	10	Between some and moderate comfort	4
Very high comfort	9	Some comfort	3
Between fairly high and high comfort	8	Between a little bit and some comfort	2
Fairly high comfort	7	A little bit of comfort	1
Between moderate and fairly high comfort	6	No comfort at all	0
Moderate comfort	5		

Table 4.1.5: Anova: Two-Factor with replication from initial time to 60 min of walking

SUMMARY	At the initial time of use	After 20 min	After 40 min	After 60 min
Control				
Count	20	20	20	20
Sum	127	114	72	43
Average	6.35	5.7	3.6	2.15
Variance	4.23	2.22	3.51	2.34
Developed				
Count	20	20	20	20
Sum	129	132	114	100
Average	6.45	6.6	5.7	5
Variance	4.89	3.41	1.69	1.05

4.2 Results and Discussion

4.2.1 Peak plantar Pressure

We constructed a prototype of JPM bed of female foot to enhance the plantar pressure distribution and to study the internal stresses in the bones during balanced standing. Figure 4.2.1 represents the peak plantar pressure distribution under different parts of forefoot obtained from the different metatarsal bed condition during balanced standing. All of the measured values and their mean showed high pressure distribution beneath the medial forefoot region during conventional or control mode of high heeled wearing. The conventional model showed a peak pressure of 14.9 N/cm2 for MF, 9.1 N/cm2 for CF, and 1.3 N/cm2 for LF. With MSEVA, the peak pressures at the forefoot area were 10.4 N/cm2, 9.9 N/cm2, and 2.0 N/cm2 respectively. The peak pressures with VSEPDM Neoprene Sponge metatarsal cup were 8.4 N/cm2, 9.3 N/cm2, and 1.6 N/cm2 respectively. On the other hand the developed prototype of JPMC showed peak planter pressures of 9.2 N/cm2, 9.8 N/cm2, and 3.0 N/cm2 respectively.

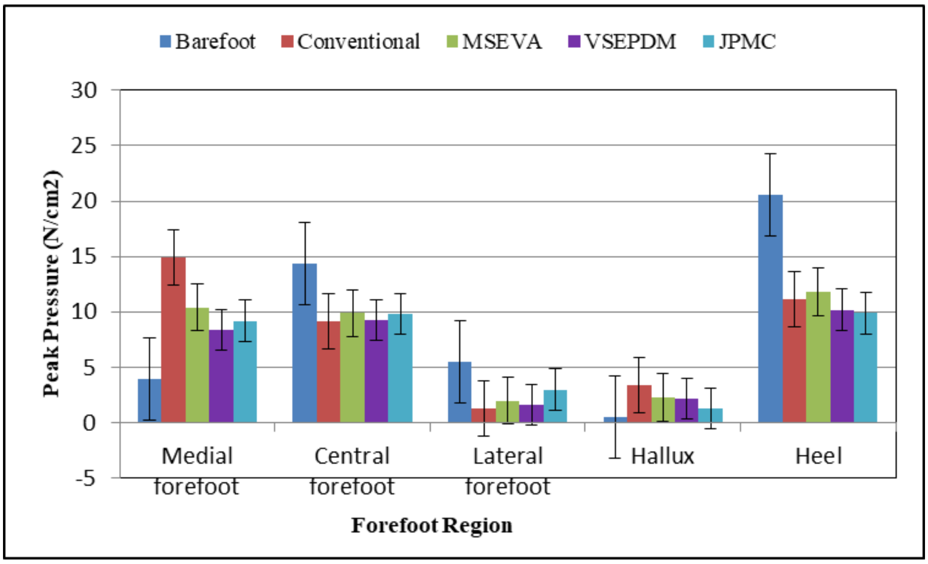


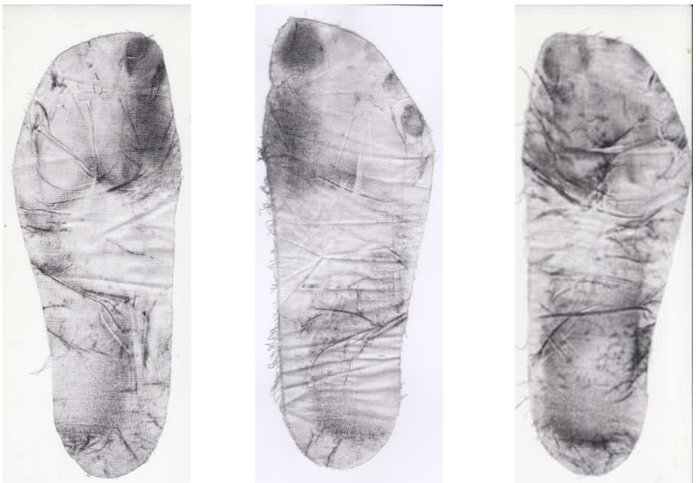
Figure 4.2.1: Peak pressures on (i) Medial Forefoot, (ii) Central Forefoot, and (iii) Lateral Foot, (iv) Hallux region, and (v) Central Heel area; under different metatarsal base conditions

Under the same loading condition, the JPMC was reduced and redistributed the peak plantar pressure at medial forefoot region. The potency of JPMC in redistributing the plantar foot pressure can be further seen in Table 4.2.1. It represents the peak plantar pressures for three different positions at forefoot area with respect to different base materials. In conventional system, the maximum of forefoot load 51.9% centralized on medial portion and the central and lateral forefoot experienced a lower amount of load 31.7% and 4.5% respectively. In case of rest three cases, the load was more widely distributed among the forefoot area. But in JPMC, the distribution pattern (39.4%, 42% and 12.8% respectively) based on total forefoot load is closer towards barefoot condition (16%, 59.2% and 22.6%). In case of VSEPDM sponge most of load 43.2% shifted to central (2nd to 3rd metatarsal head) and there is no significant improvement noticed on the lateral (5th metatarsal head) forefoot area (load 7.4%). But in case of JPMC, the lateral forefoot pressure also improved to 12.8%.

Table 4.2.1: Percentages of peak pressure coverage on the basis of total forefoot pressure with different metatarsal base condition

Condition	Medial forefoot %	Central forefoot %	Lateral forefoot %	Hallux %
Barefoot	16	59.2	22.6	2
Conventional	51.9	31.7	4.5	11.8
MSEVA	42.2	40.2	8.1	9.3
VSEPDM	39.0	43.2	7.4	10.2
JPMC	39.4	42.0	12.8	5.6

The peak pressures at the heel and hallux position also affected by the metatarsal base materials. The peak pressures during balanced standing with different base conditions at heel were 20.6 N/cm2 for barefoot, 11.1 N/cm2 for controlled, 11.8 N/cm2 for MSEVA, 10.2 N/cm2 for VSEPDM Neoprene Sponge, and 9.9 N/cm2 for the JPMC. At hallux position the respective peak pressures were 0.5 N/cm2, 3.4 N/cm2, 2.3 N/cm2, 2.2 N/cm2, and 1.3 N/cm2. Hence the stress and load decentralization in the medial forefoot was more pronounced with the use of joint padded metatarsal cup. Compared with the control metatarsal base, the medial forefoot area experienced a reduction of 9.7%, 12.9% and 12.5% respective peak pressure with the use of MSEVA, VSEPDM neoprene sponge, and JPMC. The corresponding increases of peak pressure were 8.5%, 11.5%, and 10.3% at the central forefoot and 3.6%, 2.9%, and 8.3% at lateral position. The corresponding decreases of load in the hallux were 2.5%, 1.6% and 6.2%. Though in MSEVA and VSEPDM the change of peak pressure in MF and CF was quite satisfactory, the peak pressure in LF and hallux position is not as good as JPMC. The hallux toe experienced the highest plantar pressure during conventional system which could bring about pain and foot defect [78] and lowest plantar pressure during JPMC which is closer to barefoot condition.



Conventional (left) Conventional (right) JPMC (right)

Figure 4.2.2: Carbon impression of plantar pressure distribution after 10 minutes of walking

Hence during JPMC, forefoot load was more widely distributed among medial to lateral area and at the same time the load on hallux toe was reduced remarkably.

4.2.2 Angular deformation

The results from all the participants showed that the angular displacement in hallux valgus and inter-metatarsal were maximum in conventional system and minimum in JPMC (Figure 4.2.3). The largest differences of mean deviation 7.8° in HV angles was observed between barefoot and conventional mode of metatarsal base and the smallest differences of mean 3.9° between barefoot and JPMC. Hence average hallux valgus angle reduced by JPMC approximately 41.4% than conventional system, and 28.7% than VSEPDM.

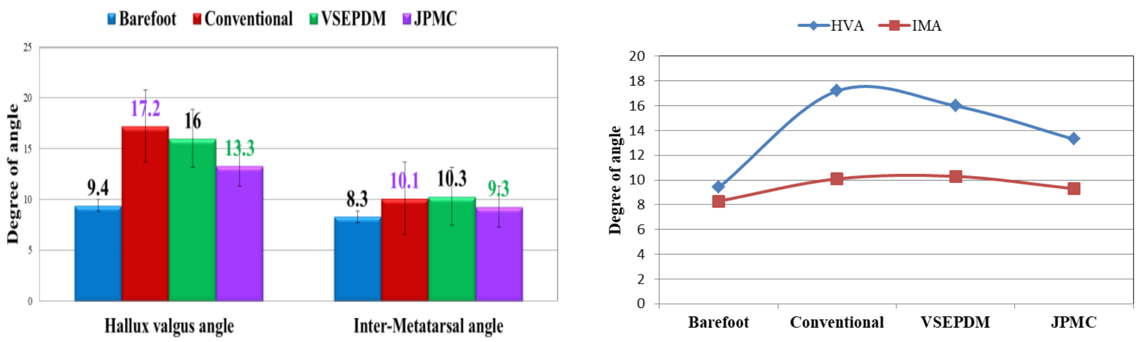


Figure 4.2.3: Angular displacements of hallux valgus and inter-metatarsal alignment with different types of metatarsal base

The IMA also increased maximum of 2°in VSEPDM, and 1.8° in conventional system and a minimum of 1° in JPM cup. This indicates that JPMC also decreased the IMA to 12%. The conventional bed of metatarsal in high heeled shoe experienced with heavy medial forefoot stress that forced the first metatarsal to the outwards. These abnormal stresses create higher HVA and IMA in high heeled female foot and lead to hallux valgus deformity [79]. Hence JPM cup helps the foot to reduce the stress by absorbing the extra load on medial forefoot region.

4.2.3 Hypothesis test for Comfort

The hypothesis test was carried out based on conventional and developed prototype of metatarsal cup. There are two types of statements about the comfort parameter were selected one is null hypothesis for matching and another is alternative hypothesis for not matching of comfort level between developed and control metatarsal pad. It might be accepted or rejected the null hypothesis based on statistical data (Table 10) of comfort rating. During initial time of wearing the footwear, there is not enough evidence to reject the null hypothesis. In this case both P-value 0.88 and t critical value 2.02 are greater than t-stat value or observation value 0.14. But after 60 minutes of use it does not have much evidence to support the null hypothesis. Here, both P-value 6.71 and t-critical value 2.03 are smaller than observation value 6.91.

Table 4.2.2: t-Test: Two-Sample assuming unequal variances

At the initial time of use		
	Developed	*Control*
Mean	6.45	6.35
Variance	4.892105263	4.239473684
Observations	20	20
Hypothesized Mean Difference	0	
df	38	
t Stat	0.147993302	
P(T<=t) two-tail	0.88313057	
t Critical two-tail	2.024394164	
After 60min of use		
	Developed	*control*
Mean	5	2.15
Variance	1.052631579	2.344736842
Observations	20	20
Hypothesized Mean Difference	0	
df	33	
t Stat	6.914941893	
P(T<=t) two-tail	6.71262E-08	
t Critical two-tail	2.034515297	

At the initial time of use most of the participants felt same comfort on both conventional and developed padded cup. The average comfort ratings at this stage were 6.35 and 6.45 which indicate moderate to fairly high comfort. At the times of 20 and 40mintutes of use the rating in the left foot getting lowered and show moderate to some comfort. But at the same time right foot was showed fairly high to moderate comfort. Finally at the time of 60 minutes the left foot with conventional base gave a comfort level of between a little bit and some comfort with 2.15 rating while joint padded metatarsal cup showed moderate comfort with 5.0 rating. This demonstrates that the rate of comfort level diminishing more slowly (Figure 4.2.4) with time in developed prototype than the conventional type of metatarsal basement area.

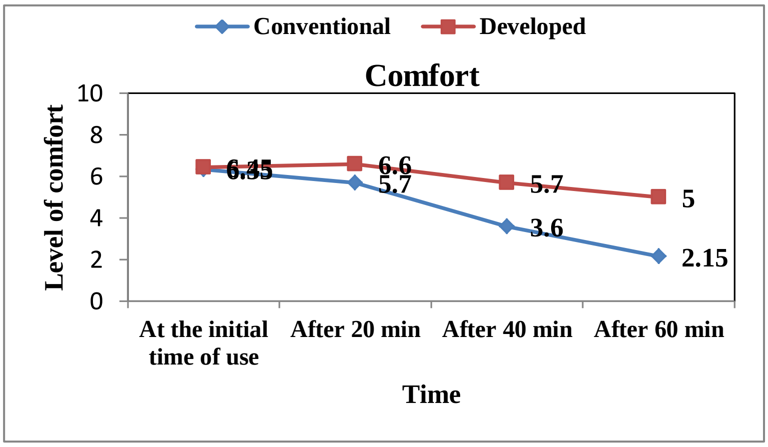


Figure 4.2.4: Level of comfort with successive time interval with (a) Conventional High heeled, and (b) Developed high heel

(a - Right Foot) **(b - Left Foot)**

Figure 4.2.5: Foot plantar face after 60 minutes of walking; a) With JPMC, and b) with conventional base

All the investigation indicates that JPMC provide extra features based on plantar pressure distribution. Plantar pressure was redistributed in case of JPMC. In this case the alignment of foot bone was taken more secured position with respect to conventional system as well as MSEVA and VSEPDM. JPMC is the combination of both MSEVA and VSEPDM. In conventional system, most of forefoot load centralized on medial side in case of high heeled footwear [8]. The combination of materials with two different softness and other properties in JPMC was given extra facilities to redistribute this forefoot pressure. The very soft EPDM sponge was used in the medial side (beneath the 1st finger) of forefoot and medium soft EVA in the central (beneath the 2nd to 4th finger) forefoot, and the rest of side lateral forefoot was faced by conventional base materials. When the load first exerted on to the medial side, the soft EPDM absorb some pressure by compressing the materials downwards. At the time of compression on medial portion, the materials in central section started to give the support through getting contact. When both the medial and central portion is saturated with pressure, they jointly tried to give downward pressure and the rest of the part by conventional base started to give their contribution in support system. Thus the plantar pressure is more widely distributed in the developed prototype of high heeled footwear. This wide distribution of forefoot load can give extra security to musculoskeletal system and can resist valgus deformity [80]. Most of the participants consent is also given the clarity about pressure distribution by enhancing comfort duration of the footwear.

CHAPTER V

Conclusions and Recommendations

5.1 Conclusion

A Joint padded metatarsal cup of the female foot was developed to redistribute the female foot plantar pressure and the internal stresses in the bony structures under high heeled condition. To compare the effectiveness of this JPMC, the conventional system and the jointing materials were investigated separately. All the analysis and comparison demonstrated that the forefoot custom moulded joint metatarsal cup has a good impact in redistributing peak plantar pressure, reducing load on medial forefoot and big toe area and improving foot functions in high heeled footwear than the conventional system or a single type of materials. From the investigation, it can be conclude that a combination of different materials with different compressive and softness can give more precise pressure distribution on foot planter surface in high heeled female footwear.

5.2 Limitations of the Study

Although the use of in-shoe plantar pressure measurement devices are a fairly common approach to studying plantar pressure distribution [81], this study did not applied the techniques and also did not provide the complete picture of these assessments. Though we attempted to examine all the available materials, this was not always possible. We have made random collection of sample for metatarsal cup. Foot Plantar response based materials selection might provide more uniform distribution of forefoot load. Furthermore, an analysis of the body posture might reveal more insight about the musculoskeletal alignment of the participants. Finally, increasing and similar number of participants for each assessment may enhance the purity and generalizability of our findings.

5.3 Implications for Future Research

Previous research revealed morphological, biomechanical, and physiological effects of humans when wearing high-heeled footwear. But still we do not have enough information about how we can reduce these effects and improve the comfort of high-heeled footwear. Present study showed that foot-bed with mixing of materials can reduce adverse effects of high heel. To optimize the negative effects it needs to study of effects of material properties on comfort. The following topics deserve further studies:

1. Investigation and comparison on angular movement of bones, acceleration of limb movement, pulse rate and oxygen saturation, centre of pressure etc. with the same kind of foot bed design

2. Study on relationships between the foot, the footwear, and the foot–footwear interaction. Efforts to reveal what foot has what kind of trouble when it wears what footwear made on what types of base materials may help to derive relationship between the foot defect and the footwear design.

3. Investigations on the effects of material properties eg., heels, soles, insoles, uppers, lining, toe puff, counter stiffener or inserts on perception of comfort or biomechanics or ergonomics of gait.

4. Research on effects of design factors of the high heel on plantar pressure distribution. If heel shapes, heel lift, toe shape, counter stiffener shape, shoe size etc. have potential effects on the plantar pressure and comfort, such information will be useful for designing comfortable and safety high-heeled footwear.

Reference

1. Hapsari, V. D., and Xiong, S., 2016, "Effects of high heeled shoes wearing experience and heel height on human standing balance and functional mobility," Ergonomics, 59(2), pp. 249-264.

2. Association, A. P. M., 2014, "Public Opinion Research on Foot Health and Care," APMAUSA, p. 5.

3. Liu, Y., and Wang, Y. T., 2004, "Reliability of the Kinetic Measures Under Different Heel Conditions During Normal Walking," Measurement in Physical Education and Exercise Science, 8(1), pp. 21-31.

4. Mika, A., Oleksy, Ł., Mika, P., Marchewka, A., and Clark, B. C., 2012, "The influence of heel height on lower extremity kinematics and leg muscle activity during gait in young and middle-aged women," Gait & Posture, 35(4), pp. 677-680.

5. Goonetilleke, R. S., 2013, The Science of Footwear, CRC Press.

6. Frey, C., Thompson, F., Smith, J., Sanders, M., and Horstman, H., 1993, "American Orthopaedic Foot and Ankle Society women's shoe survey," Foot & Ankle, 14(2), pp. 78-81.

7. Luximon, Y., Luximon, A., Yu, J., and Zhang, M., 2012, "Biomechanical evaluation of heel elevation on load transfer—experimental measurement and finite element analysis," Acta Mechanica Sinica, 28(1), pp. 232-240.

8. Cong, Y., Cheung, J. T.-M., Leung, A. K., and Zhang, M., 2011, "Effect of heel height on in-shoe localized triaxial stresses," Journal of biomechanics, 44(12), pp. 2267-2272.

9. Glasoe, W. M., Nuckley, D. J., and Ludewig, P. M., 2010, "Hallux valgus and the first metatarsal arch segment: a theoretical biomechanical perspective," Physical Therapy, 90(1), pp. 110-120.

10. Speksnijder, C. M., vd Munckhof, R. J., Moonen, S. A., and Walenkamp, G. H., 2005, "The higher the heel the higher the forefoot-pressure in ten healthy women," The Foot, 15(1), pp. 17-21.

11. Männikkö, K., and Sahlman, J., 2017, "The Effect of Metatarsal Padding on Pain and Functional Ability in Metatarsalgia," Scandinavian Journal of Surgery, 106(4), pp. 332-337.

12. Li, J., Gu, Y., Ren, X., Lake, M., and Zeng, Y., 2010, "Biomechanical effects of foam inserts on forefoot load during the high-heeled gait: A pilot study," Journal of mechanics in medicine and biology, 10(04), pp. 667-674.

13. Luximon, Y., Yu, J., and Zhang, M., 2014, "A comparison of metatarsal pads on pressure redistribution in high heeled shoes," Research journal of textile and apparel, 18(2), pp. 40-48.

14. Paton, J., Woodrow, T., and Passmore, C., 2007, "The effect of plantar cover padding with U'd cut-out on plantar foot pressure; a preliminary study," British Journal of Podiatry, 10(3), pp. 110-116.

15. Curran, M. J., Ratcliffe, C., and Campbell, J., 2015, "A comparison of types and thicknesses of adhesive felt padding in the reduction of peak plantar pressure of the foot: a case report," Journal of medical case reports, 9(1), p. 203.

16. Swierzewski, J. J., 2000, "Anatomy: Foot and Ankle," https://web.archive.org/web/20090831015134/http://www.podiatrychannel.com/anatomy/index.shtml.

17. OpenStax, 2013, "ANATOMY AND PHYSIOLOGY: Chapter 8. The Appendicular Skeleton: Bones of the Lower Limb: ," https://opentextbc.ca/anatomyandphysiology/chapter/8-4-bones-of-the-lower-limb/.

18. footEducation, 2015, "Bones and Joints of the Foot and Ankle Overview," https://footeducation.com/bones-and-joints-of-the-foot-and-ankle-overview/.

19. Schrum, C., 2008, "high heels: so sexy it hurts," the lowa source.

20. Morris, P. H., White, J., Morrison, E. R., and Fisher, K., 2013, "High heels as supernormal stimuli: How wearing high heels affects judgements of female attractiveness," Evolution and Human Behavior, 34(3), pp. 176-181.

21. Tonchi, S., and Weber, C., 2014, Killer heels: the art of the high-heeled shoe, Prestel Verlag.

22. Barnish, M., Morgan, H. M., and Barnish, J., 2018, "The 2016 HIGh Heels: Health effects And psychosexual BenefITS (HIGH HABITS) study: systematic review of reviews and additional primary studies," BMC public health, 18(1), p. 37.

23. Tyler, T. U. o. T. H. S. C. a., 2007, "Hazards of High Heels."

24. Ivey, B., 2006, "High-heel hazards," South Florida Sun-sentinel.

25. protectors, H. h., 2014, "25 Types of Heels: The Ultimate Guide."

26. leaf, 2018, "Materials Used in Making the Heels & Soles of Shoes," https://www.leaf.tv/articles/materials-used-in-making-the-heels-soles-of-shoes/.

27. Dhukaram, V., Hossain, S., Sampath, J., and Barrie, J., 2002, "Correction of hammer toe with an extended release of the metatarsophalangeal joint," The Journal of bone and joint surgery. British volume, 84(7), pp. 986-990.

28. español, L. e., "Varicose Veins," National Heart, Lung, and Blood Institute.

29. Solutions, A. H., 2018, "Foot pain," Medical Encyclopedia, MedlinePlus; Trusted Health Information for you.

30. Russell, B. S., 2010, "The effect of high-heeled shoes on lumbar lordosis: a narrative review and discussion of the disconnect between Internet content and peer-reviewed literature," Journal of chiropractic medicine, 9(4), pp. 166-173.

31. Foster, A., Blanchette, M. G., Chou, Y.-C., and Powers, C. M., 2012, "The influence of heel height on frontal plane ankle biomechanics: implications for lateral ankle sprains," Foot & ankle international, 33(1), pp. 64-69.

32. Russell, B. S., Muhlenkamp, K. A., Hoiriis, K. T., and DeSimone, C. M., 2012, "Measurement of lumbar lordosis in static standing posture with and without high-heeled shoes," Journal of chiropractic medicine, 11(3), pp. 145-153.

33. Zorina Galis, D. R., and Suman M. Wasan, 2018, "Varicose veins and spider veins," Office on womens health.

34. Solutions, A. H., "Hammer toe," Medical Encyclopedia, MedlinePlus; Trusted health Information for you.

35. Giaconi, R., Questad, K., Ko, M., and Lehmann, J., 1991, "Footwear and posture. Compensatory strategies for heel height," american Journal of physical Medicine & Rehabilitation, 70(5), pp. 246-254.

36. Snow, R. E., and Williams, K. R., 1994, "High heeled shoes: their effect on center of mass position, posture, three-dimensional kinematics, rearfoot motion, and ground reaction forces," Archives of physical medicine and rehabilitation, 75(5), pp. 568-576.

37. Esenyel, M., Walsh, K., Walden, J. G., and Gitter, A., 2003, "Kinetics of high-heeled gait," Journal of the American Podiatric Medical Association, 93(1), pp. 27-32.

38. Opila-Correia, K., 1990, "Kinematics of high-heeled gait," Archives of physical medicine and rehabilitation, 71(5), pp. 304-309.

39. Adrian, M. J., and Karpovich, P. V., 1966, "Foot instability during walking in shoes with high heels," Research Quarterly. American Association for Health, Physical Education and Recreation, 37(2), pp. 168-175.

40. Stefanyshyn, D. J., Nigg, B. M., Fisher, V., O'Flynn, B., and Liu, W., 2000, "The influence of high heeled shoes on kinematics, kinetics, and muscle EMG of normal female gait," Journal of Applied Biomechanics, 16(3), pp. 309-319.

41. Kouchi, M., and Tsutsumi, E., 2000, "3D foot shape and shoe heel height," Anthropological Science, 108(4), pp. 331-343.

42. Schwartz, R. P., and Heath, A. L., 1959, "Preliminary findings from a roentgenographic study of the influence of heel height and empirical shank curvature on osteo-articular relationships in the normal female foot," JBJS, 41(6), pp. 1065-1076.

43. Merrifield, H., 1971, "Female gait patterns in shoes with different heel heights," Ergonomics, 14(3), pp. 411-417.

44. Broch, N. L., Wyller, T., and Steen, H., 2004, "Effects of heel height and shoe shape on the compressive load between foot and base: A graphic analysis of principle," Journal of the American Podiatric Medical Association, 94(5), pp. 461-469.

45. Hong, W.-H., Lee, Y.-H., Chen, H.-C., Pei, Y.-C., and Wu, C.-Y., 2005, "Influence of heel height and shoe insert on comfort perception and biomechanical performance of young female adults during walking," Foot & ankle international, 26(12), pp. 1042-1048.

46. Yung-Hui, L., and Wei-Hsien, H., 2005, "Effects of shoe inserts and heel height on foot pressure, impact force, and perceived comfort during walking," Applied ergonomics, 36(3), pp. 355-362.

47. Ono, H., 1969, "Heel height and muscle activity," Journal of the Japanese Orthopedic Association, 43, pp. 527-547.

48. Lord, S. R., and MBBS, G. M. B., 1996, "Shoe characteristics and balance in older women," Journal of the American Geriatrics Society, 44(4), pp. 429-433.

49. Healey, K., and Chen, K., 2010, "Plantar fasciitis: current diagnostic modalities and treatments," Clinics in podiatric medicine and surgery, 27(3), pp. 369-380.

50. Corrigan, J. P., Moore, D. P., and Stephens, M. M., 1993, "Effect of heel height on forefoot loading," Foot & Ankle, 14(3), pp. 148-152.

51. Mandato, M., and Nester, E., 1999, "The effects of increasing heel height on forefoot peak pressure," Journal of the American Podiatric Medical Association, 89(2), pp. 75-80.

52. Goonetilleke, R. S., 1999, "Footwear cushioning: relating objective and subjective measurements," Human Factors, 41(2), pp. 241-256.

53. Grier, T. L., Knapik, J. J., Swedler, D., and Jones, B. H., 2011, "Footwear in the United States Army Band: Injury incidence and risk factors associated with foot pain," The Foot, 21(2), pp. 60-65.

54. Miller, J. E., Nigg, B. M., Liu, W., Stefanyshyn, D. J., and Nurse, M. A., 2000, "Influence of foot, leg and shoe characteristics on subjective comfort," Foot & ankle international, 21(9), pp. 759-767.

55. Witana, C. P., Goonetilleke, R. S., Au, E. Y. L., Xiong, S., and Lu, X., 2009, "Footbed shapes for enhanced footwear comfort," Ergonomics, 52(5), pp. 617-628.

56. Beely, F., 1882, "Zur Mechanik des Stehens. Uber die Beddeutung des Fussgewolbes beim Stehen," Langenbecks Arch. klin. Chirur., 27, pp. 457-471.

57. Hills, A., Hennig, E., McDonald, M., and Bar-Or, O., 2001, "Plantar pressure differences between obese and non-obese adults: a biomechanical analysis," International journal of obesity, 25(11), p. 1674.

58. Bellizzi, M., Rizzo, G., Bellizzi, G., Ranieri, M., Fanelli, M., Megna, G., and Procoli, U., 2011, "Electronic baropodometry in patients affected by ocular torticollis," Strabismus, 19(1), pp. 21-25.

59. Kaercher, C. W., Genro, V. K., Souza, C. A., Alfonsin, M., Berton, G., and Cunha Filho, J. S., 2011, "Baropodometry on women suffering from chronic pelvic pain-a cross-sectional study," BMC women's health, 11(1), p. 51.

60. Chapman, J., Preece, S., Braunstein, B., Höhne, A., Nester, C., Brueggemann, P., and Hutchins, S., 2013, "Effect of rocker shoe design features on forefoot plantar pressures in people with and without diabetes," Clinical Biomechanics, 28(6), pp. 679-685.

61. Melvin, J., Preece, S., Nester, C., and Howard, D., 2014, "An investigation into plantar pressure measurement protocols for footwear research," Gait & posture, 40(4), pp. 682-687.

62. Saito, M., Nakajima, K., Takano, C., Ohta, Y., Sugimoto, C., Ezoe, R., Sasaki, K., Hosaka, H., Ifukube, T., and Ino, S., 2011, "An in-shoe device to measure plantar pressure during daily human activity," Medical engineering & physics, 33(5), pp. 638-645.

63. Crea, S., Donati, M., De Rossi, S. M. M., Oddo, C. M., and Vitiello, N., 2014, "A wireless flexible sensorized insole for gait analysis," Sensors, 14(1), pp. 1073-1093.

64. Motha, L., Kim, J., and Kim, W. S., 2015, "Instrumented rubber insole for plantar pressure sensing," Organic Electronics, 23, pp. 82-86.

65. Tan, A. M., Fuss, F. K., Weizman, Y., Woudstra, Y., and Troynikov, O., 2015, "Design of low cost smart insole for real time measurement of plantar pressure," Procedia Technology, 20, pp. 117-122.

66. Varoto, R., Oliveira, G. C., de Lima, A. V. F., Critter, M. M., and Cliquet Jr, A., "A Low Cost Wireless System to Monitor Plantar Pressure using Insole Sensor: Feasibility Approach," Proc. BIODEVICES, pp. 207-214.

67. Yun, M. H., Donges, L., and Freivalds, A., 1992, "Using force sensitive resistors to evaluate the driver seating comfort," Advances in Industrial Ergonomics and safety IV, pp. 403-410.

68. Smith, B. T., Coiro, D. J., Finson, R., Betz, R. R., and McCarthy, J., 2002, "Evaluation of force-sensing resistors for gait event detection to trigger electrical stimulation to improve walking in the child with cerebral palsy," IEEE Transactions on Neural Systems and Rehabilitation Engineering, 10(1), pp. 22-29.

69. Pawin, J., Khaorapapong, T., and Chawalit, S., "Neural-based human's abnormal gait detection using force sensitive resistors," Proc. Advanced Computational Intelligence (IWACI), 2011 Fourth International Workshop on, IEEE, pp. 224-229.

70. Sayed, M., Garcia, J. C. D., and Alboul, L., "Texture recognition using force sensitive resistors," Proc. Conference Towards Autonomous Robotic Systems, Springer, pp. 288-294.

71. Hayda, R., Tremaine, M. D., Tremaine, K., Banco, S., and Teed, K., 1994, "Effect of metatarsal pads and their positioning: a quantitative assessment," Foot & ankle international, 15(10), pp. 561-566.

72. Van Hamme, A., Samson, W., Dohin, B., Dumas, R., and Chèze, L., 2013, "Influence of heel height, upper height and sole stiffness on shod walking in young children," Footwear Science, 5(sup1), pp. S69-S70.

73. Yang, L., Hao, F., Yan, H., Ran, M., Yan, S., and Chen, W., 2013, "Effect of midsole material on plantar pressure of high-heel shoes," Footwear Science, 5(sup1), pp. S59-S61.

74. Interlink-Electronics, "FSR- Force Sensing Resistors," Integration Guide and evaluation catalog, Interlink Electronics, Inc., USA, p. 33.

75. Noya, F., 2017, "Sensor design: Smart insole for diabetic people," https://hackaday.io/project/27056-ebers/log/66516-sensor-design.

76. Gu, Y., Rong, M., and Ruan, G., 2011, "The outsole pressure distribution character during high-heeled walking," Procedia Environmental Sciences, 8, pp. 464-468.

77. Mann, R. A., 1995, "Disorders of the first metatarsophalangeal joint," JAAOS-Journal of the American Academy of Orthopaedic Surgeons, 3(1), pp. 34-43.

78. Bae, Y.-H., Ko, M., and Lee, S. M., 2015, "The influence of revised high-heeled shoes on foot pressure and center of pressure during standing in young women," Journal of physical therapy science, 27(12), pp. 3745-3747.

79. Coughlin, M. J., 1984, "Hallux valgus," Postgraduate Medicine, 75(5), pp. 174-187.

80. Eshraghi, S., Esat, I., and Mohagheghi, A. A., 2015, "Relationship between Hallux Valgus and plantar force transformation among metatarsal regions," Footwear Science, 7(sup1), pp. S151-S152.

81. Giacomozzi, C., 2010, "Appropriateness of plantar pressure measurement devices: a comparative technical assessment," Gait & posture, 32(1), pp. 141-144.

Appendix:

Data Collection table for Plantar Pressure Measurement

Table 1: Pressure distribution at different position of female foot plantar surface					
Materials	Heel (N/cm2)	Medial forefoot (1^{st} Finger) (N/cm2)	Central forefoot (2-4 finger) (N/cm2)	Lateral forefoot (5^{th} finger) (N/cm2)	Hallux (N/cm^2)
Barefoot					
Control					
Medium soft Eva					
Very soft EPDM Neoprene sponge					
Joint rubber pad					

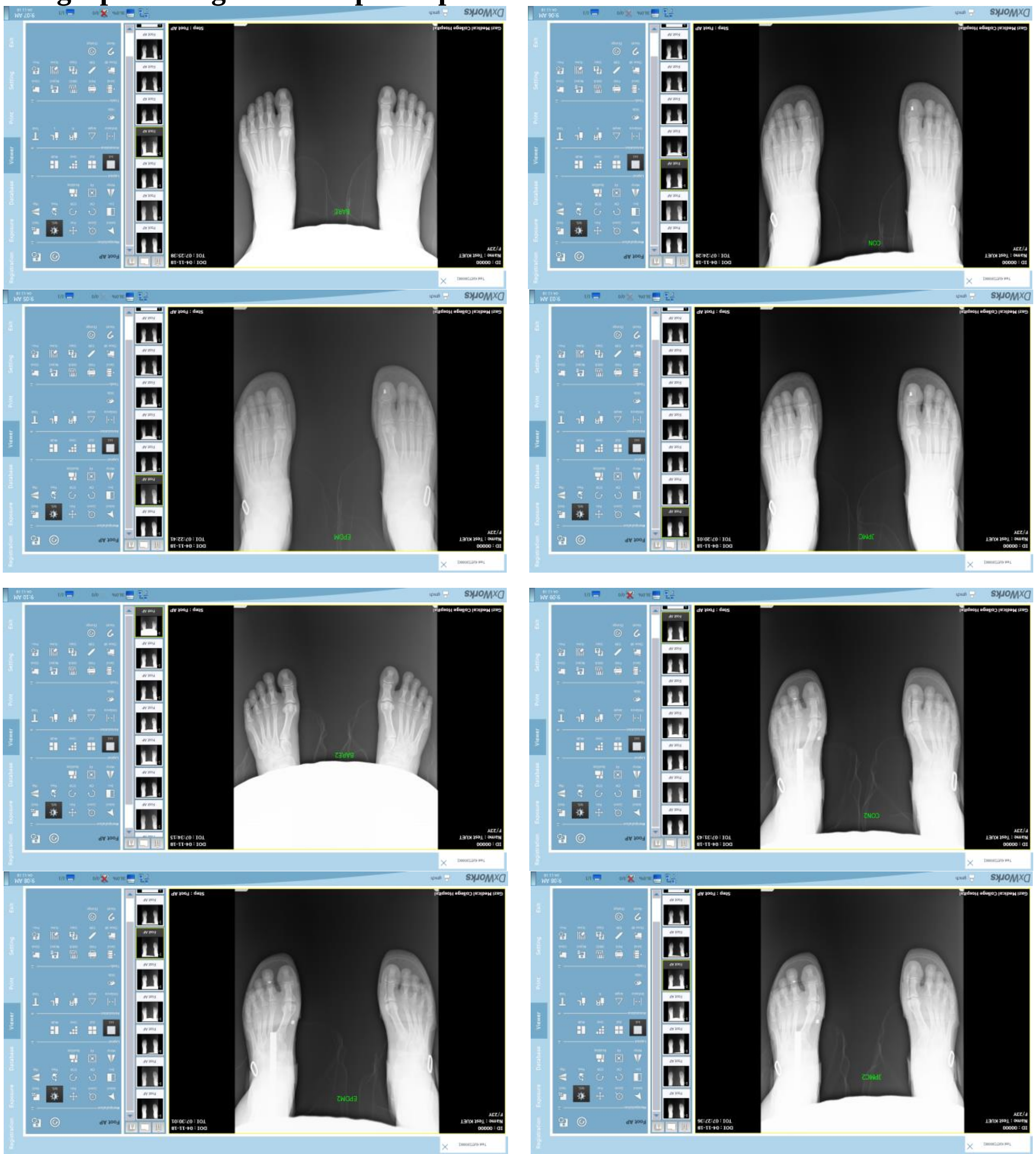
Testing Guide table for Radiographic Assessment

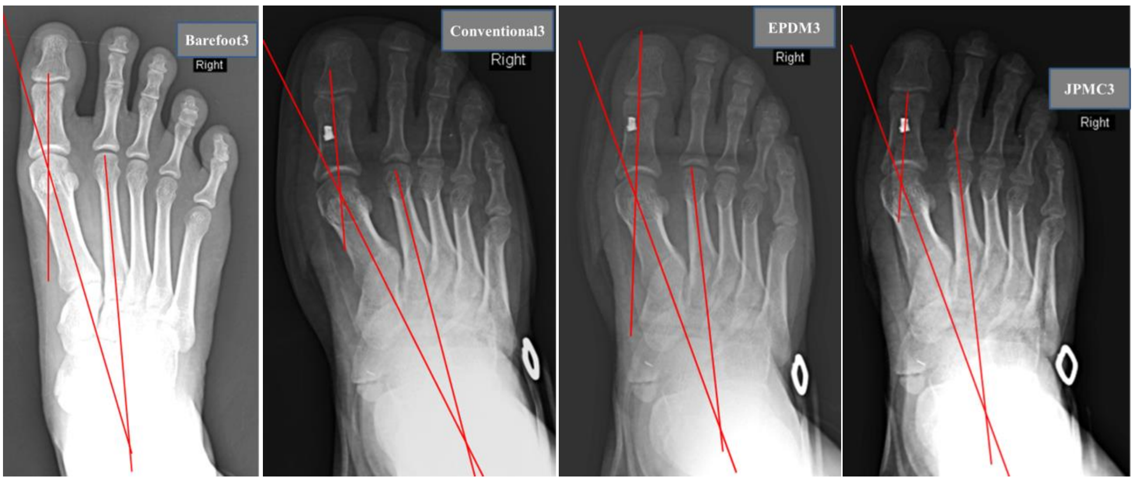
Table 2. Experimental guide for radiographic test			
Position		**Footwear set up**	
		Left Foot	**Right foot**
A	**Anteroposterior** view of barefoot	Barefoot	Barefoot
B	**Anteroposterior** view of the female foot wearing high-heel	Conventional	Metatarsal cup with control mode
C	**Anteroposterior** view of the female foot wearing high-heel	Conventional	Metatarsal cup with VSEPDM Neoprene sponge
D	**Anteroposterior** view of the female foot wearing high-heel	Conventional	Joint padded metatarsal cup

Data Collection table for Radiographic Assessment

Table 3. Angular displacement of Hallux valgus angle (HVA) and Inter-Metatarsal angle (IMA)					
Value	Participants	Barefoot	Conventional	VSEPDM	JPMC
HVA					
IMA					

Radiographic Imagers for all participants





Data Collection table for consumer survey

Survey for Comfort of High Heeled Footwear

A Survey on female consumers of high heeled footwear for comfort based on questionnaire below -

Physical characteristics of female participants

	Value	Remarks
Age		
Height		
Weight		
Shoe size		

1.0 Please rate your total comfort from 0 to 10, using the scale below

At the starting time of use

The amount of total comfort you are experiencing **right now:**	Rating	Place "X" in best box below	
		Left foot	**Right foot**
Highest comfort possible	10		
Very high comfort	9		
Between fairly high and high comfort	8		
Fairly high comfort	7		
Between moderate and fairly high comfort	6		
Moderate comfort	5		
Between some and moderate comfort	4		
Some comfort	3		
Between a little bit and some comfort	2		
A little bit of comfort	1		
No comfort at all	0		

After 20 minutes of use

The amount of total comfort you are experiencing **right now:**	Rating	Place "X" in best box below	
		Left foot	**Right foot**
Highest comfort possible	10		
Very high comfort	9		
Between fairly high and high comfort	8		
Fairly high comfort	7		
Between moderate and fairly high comfort	6		
Moderate comfort	5		
Between some and moderate comfort	4		
Some comfort	3		
Between a little bit and some comfort	2		
A little bit of comfort	1		
No comfort at all	0		

After 40 minutes of use

The amount of total comfort you are experiencing **right now:**	Rating	Place "X" in best box below	
		Left foot	**Right foot**
Highest comfort possible	10		
Very high comfort	9		
Between fairly high and high comfort	8		
Fairly high comfort	7		
Between moderate and fairly high comfort	6		
Moderate comfort	5		
Between some and moderate comfort	4		
Some comfort	3		
Between a little bit and some comfort	2		
A little bit of comfort	1		
No comfort at all	0		

After 60 minutes of use

The amount of total comfort you are experiencing **right now:**	Rating	Place "X" in best box below	
		Left foot	**Right foot**
Highest comfort possible	10		
Very high comfort	9		
Between fairly high and high comfort	8		
Fairly high comfort	7		
Between moderate and fairly high comfort	6		
Moderate comfort	5		
Between some and moderate comfort	4		
Some comfort	3		
Between a little bit and some comfort	2		
A little bit of comfort	1		
No comfort at all	0		

Note: Total Comfort includes physical, psychological, spiritual and social aspects of comfort, all combined into one score.